Konferenzbeiträge / Atti / Proceedings

Building Simulation Applications BSA 2019

4th IBPSA-Italy Conference
Bozen-Bolzano, 19th–21st June 2019

Edited by
Giovanni Pernigotto, Francesco Patuzzi,
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1st edition
www.unibz.it/universitypress

ISSN 2531-6702
ISBN 978-88-6046-176-6

Design and Evaluation of Extreme Moisture Reference Years for Moisture-Related Risk Assessments

Michele Libralato – University of Udine, Italy – libralato.michele.1@spes.uniud.it
Giovanni Pernigotto – Free University of Bozen-Bolzano, Italy – giovanni.pernigotto@unibz.it
Alessandro Prada – University of Trento, Italy – alessandro.prada@unitn.it
Alessandra De Angelis – University of Udine, Italy – alessandra.deangelis@uniud.it
Onorio Saro – University of Udine, Italy – onorio.saro@uniud.it
Andrea Gasparella – Free University of Bozen-Bolzano, Italy – andrea.gasparella@unibz.it

Abstract

The risk analysis of moisture-related damages can potentially be carried out with the use of heat and moisture transfer simulations. These models require weather files as boundary conditions but, for most locations, the only weather files available are Typical Reference Years, for instance the TRY_{EN} defined in accordance with EN ISO 15927-4:2005. These reference years do not provide the critical conditions that should be used in risk assessments. In this work, two procedures to define Extreme Moisture Reference Years (ERY_{m1} and ERY_{m2}) are presented. ERY_{m1} and ERY_{m2} are designed to generate critical weather files to be used in simulations for the assessment of moisture related risks. The presented procedures are structure-independent and suitable for risk assessments that involve high air moisture content and low air temperature values. In order to assess the capabilities of ERY_m, five types of walls with different materials are simulated, considering three Italian climates (those of Gemona del Friuli, of Legnaro and of Trento) and four wall orientations (North, East, South, West). The results of simulations with ERY_{m1} and ERY_{m2} as weather files showed higher wall moisture contents and interstitial moisture accumulation risks than those with TRY_{EN}. This suggests that ERY_m could be used as a valid alternative to the TRY_{EN} in decision making frameworks and legislations that cannot include the *ad hoc* definition of a weather file for each structure, exposure and location.

1. Introduction

The boundary conditions of building energy simulations are usually defined using reference year weather files, which are meant to represent typical meteorological years, excluding extreme events. When it is required by legislation or for an evaluation framework to perform a risk analysis involving extreme events, such weather files should not be taken into consideration. For this reason the standard EN ISO 13788:2012 (CEN, 2012), describing the Glaser method procedure, prescribes the use of the mean monthly temperature values likely to occur once every 10 years and, if the only available weather file is a representative year, it recommends subtracting 2 K from the external air temperatures during the heating period and adding 2 K during the cooling period.

The Glaser method, even with strong limitations, is considered by designers to be generally conservative, even though that is not always true (Libralato et al., 2019a), and is still used as risk assessment method for interstitial moisture accumulation. However, when the limitations of the Glaser method are met, the advanced approach of the standard EN 15026:2007 (CEN, 2007) should be used. This method can also be used for other risk assessment procedures, dependent on the moisture content of the materials (for example, the corrosion risk of metal inclusions, wood decay or freeze-thaw damage). According to the standard EN 15026:2007, the weather files should be chosen based on the nature of the problem that is being investigated. The evaluation of a damage risk requires a reference weather file with extreme conditions, to allow for a conservative design of the analyzed structure. By comparison, using a representative year, for example the Test Reference Year TRY_{EN} presented in the standard EN ISO 15927-4:2005 (CEN, 2005) provides a reference year representative of the typical weather of location under consideration. The EN 15026:2007 suggests to use the "Moisture Design Reference Year", a weather file that allows to design building envelopes that reach failure at an acceptable rate, for example once every ten years. Such a reference year should be selected among the years measured in a multi-year period according to the problem under investigation. The standard provides three examples:

- For **low temperature problems,** the year with the mean temperature closest to the 10th percentile value of the distribution of the annual mean temperatures should be used;
- For **high temperature problems**, the reference year should be that with a mean temperature closest to the 90th percentile value of the distribution of the annual mean temperatures;
- For **rain penetration problems,** the reference year should have an annual rainfall value closest to the 90th percentile of annual rainfall values.

The problem of the choice of this weather year is related to the fact that the results of the risk analysis are strongly dependent on the building structure, the materials and the type of risk considered. In each location, each structure could reach failure in different years. To overcome this problem, a weather selection method was proposed by Kalamees and Vinha (2004), based on the saturation deficit parameter which is not structure-dependent. A more recent structure-dependent approach was presented by Zhou et al. (2016), who adopted a Climate Index for a preliminary selection of three weather years, which were used to run risk assessment simulations and, subsequently, to complete the design-year identification.

Other structure-independent approaches were presented by Libralato et al. (2018 and 2019b) with methodologies based on Murano et al. (2018), derived from the Finkelstein-Shafer statistic (Finkelstein and Schafer, 1971). The produced Moisture Reference Years used to perform interstitial moisture accumulation analysis on walls made of different materials obtained risk values that were more conservative than the ones obtained with the Typical Meteorological Years.

In this work, following the procedure proposed by Pernigotto et al. (2019a, 2019b) for the development of Extreme Reference Years ERY, two extreme moisture reference years, ERY_{m1} and ERY_{m2}, are proposed for the assessment of moisture-related risks. The approach is based on the method outlined in EN ISO 15927-4:2005 and uses the Finkelstein-Schafer statistics for the generation of reference years, which are built as a series of 12 months from a multi-year series of at least 10 years. Instead of looking for typicality and using all EN ISO 15927-4:2005-recommended weather variables (i.e. dry-bulb air temperature, relative humidity, global horizontal irradiance and wind speed), the statistics are exploited to identify those candidate months in the multi-year series characterized by anomalous trends and to focus only on air temperature and air humidity. Specifically, those months described by lower temperatures and higher air humidity ratios were targeted for inclusion in the ERY_m.

2. Method

The multi-year weather records from three locations in Northern Italy are considered:

- Gemona del Friuli (Udine, Friuli-Venezia Giulia; also referred to in figures as "Gemona" for brevity), provided by ARPA FVG (OSMER) - series from 2000 to 2018;
- Legnaro (Padova, Veneto), provided by ARPA Veneto - series from 2008 to 2018;
- Trento (Trentino-Alto Adige/Südtirol), provided by the Autonomous Province of Trento (IASMA Fondazione Edmund Mach) - series from 1986 to 2014.

The multi-year weather data was analyzed and checked for errors and outliers following the procedure adopted in previous works (Pernigotto et al., 2014; Antonacci and Todeschini, 2013), in compliance with the WMO Guide (WMO, 2008).

2.1 Extreme Reference Years Generation

The EN ISO 15927-4:2005 method and new approaches presented in this paper were applied for the generation of the TRY_{EN}, ERY_{m1} and ERY_{m2} weather files for the three weather stations. These generation procedures are statistical criteria to select the most or least representative months in the multi-year weather record. The TRY_{EN} generation method considers dry-bulb air temperature, relative humidity, and solar irradiance as primary variables, and wind speed as a secondary variable. It is designed to obtain a reference year that is intended to be the most representative of the full multi-year series. The ERY_{m1} was obtained with a similar procedure but considering only the dry-bulb air temperature and the humidity ratio as primary variables. The selected months were the least representative of the multi-year weather record with a monthly mean air humidity ratio higher than the multi-year weather record mean for the considered month (for example, the mean humidity ratio of all the months of January). The same procedure was followed for the ERY_{m2}, considering as primary variable the humidity ratio. For the generation of the ERY_m from the multi-year series, the following procedure was used. A general variable p is used to describe the procedure.

1. The daily means $\underline{p}$ are calculated for the primary climatic parameter p (for example dry-bulb air temperature or humidity ratio) for the whole multi-year.
2. The cumulative distribution function $\Phi(p,m,i)$ of the daily means $\underline{p}$ over the whole multi-year series for each day i of a selected calendar month m, for each p must be defined sorting the means $\underline{p}$ from the smallest to the greatest. The index i represents the order number of a day in the multi-year, from 1 to N (total number of days in the multi-year). The function Φ is obtained from the ranking $K(\underline{p},m,i)$ of the i^{th} day:

$$\Phi(p,\ m,\ i) = \frac{K(i)}{N+1} \qquad (1)$$

3. The cumulative distribution function $F(p,y,m,i)$ is calculated for the daily means within each calendar month m of each year y. $J(p,y,m,i\ )$ is the rank order of the i^{th} day obtained by ordering the daily means $\underline{p}$ within the calendar month m and the year y:

$$F(p,y,m,i) = \frac{J(p,y,m,i)}{n+1} \qquad (2)$$

   where n is the number of days of the m calendar month under consideration.
4. The Finkelstein-Shafer statistic is calculated for each climatic parameter p and each calendar month m and year y in the multi-year series as:

$$F_S(p,y,m) = \sum_{n}^{i=1} |F(p,y,m,i) - \Phi(p,m,i)| \qquad (3)$$

5. One climatic parameter p at a time is considered for each calendar month m, and sorted by increasing $F_S(p,y,m)$ values. For each of these, the ranks R are calculated and summed, creating a total ranking.
6. The first months of the ranking are the most representative of the multi-year series, while the last months are the least representative. For the composition of the TRY_{EN}, the most representative months are chosen, while for the ERY_{m1} and ERY_{m2}, the least representative months are selected. To avoid choosing the least representative months with lower air humidity ratio average values, a secondary selection of the months is performed by comparing the average humidity ratio values.

The selected months are assembled in a single year and the discontinuities between consecutive months are smoothed with a cubic interpolation of the last 8 hours and the first 8 hours of following month. As may be noted, the ERY_m procedure is similar to the TRY_{EN} procedure in EN ISO 15927-4:2005, except for point 6. The standard procedure produces a ranking which uses, as primary variables, dry-bulb air temperature, relative humidity and solar irradiance from the first (most representative) months of the ranking, and a secondary selection based on the wind speed is performed. The ERY_{m1} is obtained by considering the last (least representative) months of the ranking obtained using the dry-bulb air temperature and humidity ratio and the secondary selection is performed by comparing the mean of the humidity ratio values. The ERY_{m2} is obtained using a similar procedure, considering only the humidity ratio as a primary variable and not the dry-bulb air temperature.

2.2 Extreme Reference Year Evaluation

The proposed procedure attempts to generate weather files composed of actual measurements that respect the correlation between the weather variables and that should reproduce the extreme meteorological conditions that were registered in a location. In Pernigotto et al. (2019a), the reference years are designed to include warmer summers and colder winters while in Pernigotto et al. (2019b), extreme hot and cold reference years are suggested. In this work, the ERY_{m1} and ERY_{m2} are selected to obtain the highest humidity ratio values from the whole year. The success of the selection is first evaluated by a comparison of the monthly averages of the dry-bulb air temperature and of the air humidity ratio, then by the comparison between the results of moisture transfer simulations.

The resulting TRY_{EN} and ERY_m weather files were used as input for heat and moisture transfer simulations with the software Delphin 6 (Nicolai, 2007) in a moisture-related risk analysis of a set of three typical Italian walls, with two single-material walls used as a reference. The simulations were first performed without considering the rainfall intensity for four wall orientations (North, East, South and West). Subsequently, simulations with rainfall were performed, but only for Gemona del Friuli, due to the lack of availability of weather data for the other locations. The walls considered were (1) a well-insulated timber wall with a vapor barrier and an air gap, generally used to model X-LAM construction system, (2) an insulated hollow brick wall with two layers of hollow brick separated by an air gap and by the insulation, with a limited thermal resistance, and (3) a stone wall, with a layer of interior insulation and internal and external finishes. Two single-material walls were also simulated, in order to provide two simple results to be used as a reference. The two single layer walls were 20 cm thick, one made of concrete and the other of timber. The hygro-thermal properties of the walls are presented in Table 1.

In addition, two different indoor boundary conditions were considered in the simulation: the typical residential dwelling (normal moisture load according to WTA 6.2 guidelines, with the relative humidity values included between 20% and 60%) and a case characterized by larger indoor humidity generations (high moisture load according to WTA 6.2 guidelines, with the relative humidity values included between 40% and 70%). The results were expressed in terms of annual moisture content in the walls and occurrences of interstitial moisture accumulation. The findings obtained with the typical year TRY_{EN} were compared to those with the extreme years, ERY_{m1} and ERY_{m2}. For Gemona del Friuli, the simulations carried out also considered rainfall.

Table 1 - Properties of the walls used in the simulations

Wall	d_{tot} (cm)	U_{tot} (W m^{-2} K^{-1})	$S_{d,tot}$ (m)
Timber wall (TW)	53	0.13	56
Hollow brick wall (HB)	51	0.36	8
Stone wall (SW)	34	0.19	4
Concrete layer (CONC)	20	10.50	15
Timber layer (TIMB)	20	1.75	4

3. Results

The results highlight how the choice of weather file is of primary importance in heat and mass transfer simulations, in particular when the goal is to assess the risks related to moisture condensation and accumulation across the opaque components and on their surfaces.

3.1 Weather File Comparison

The years ERY_{m1} and ERY_{m2} for the three locations under consideration were compared in terms of monthly average dry-bulb temperature values and monthly average air humidity ratio. The comparisons showed a general agreement with the month selection criteria:

- **ERY_{m1}**: extreme values dry-bulb air temperature (lower values) and humidity ratio (higher values);
- **ERY_{m2}**: extreme humidity ratio values (higher values);
- **TRY_{EN}**: representative values of temperature and relative humidity.

In Fig. 1a, the air temperatures for the three reference years of Legnaro are presented. The TRY_{EN} temperature values are generally lower than for the ERY_{m1}, while the ERY_{m2} temperatures are not constrained by the selection method. In Fig. 1b, the average monthly humidity ratio values for the three reference years for the same location show that the in ERY_{m2}, the air humidity ratio is higher than in the TRY_{EN}, while the ERY_{m1} values are fall between the two, which is expected, as the selection procedure also involves the air temperature values.

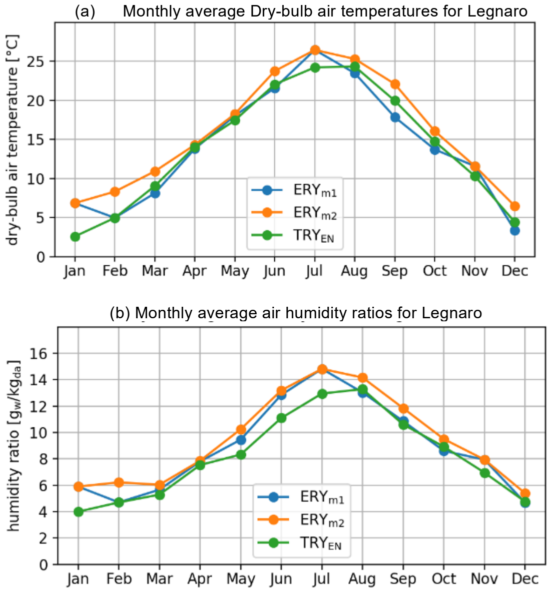

Fig. 1 – Monthly average dry-bulb air temperatures (a) and air humidity ratio monthly averages (b) for the reference years obtained for the location of Legnaro

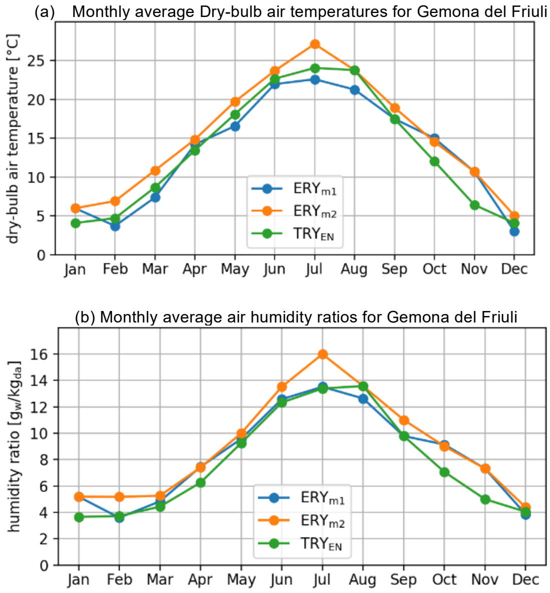

Fig. 2 – Monthly average dry-bulb air temperatures (a) and air humidity ratio monthly averages (b) for the reference years obtained for the location of Gemona del Friuli

Similar behaviors were found for Gemona del Friuli (Fig. 2), while for Trento the TRY_{EN} presented some extreme values during the year (Fig. 3). This is because some of the selected months in the reference year included extreme weather events. This feature of the data was presented and discussed in Pernigotto et al., (2019a, 2019b). The effect of the selection on an annual base is presented in Fig. 4, in terms of the means of the air humidity ratio values. In each case, the air humidity ratio is lower for the TRY_{EN} and the ERY_{m1} values are lower than for the ERY_{m2}.

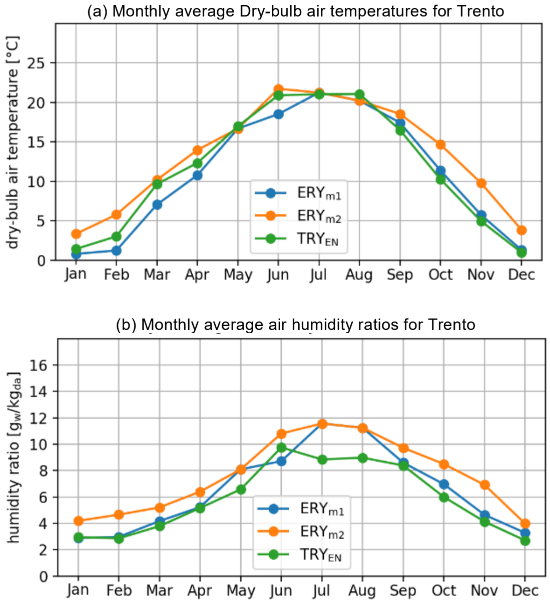

Fig. 3 – Monthly average dry-bulb air temperatures (a) and monthly average air humidity ratios (b) for the reference years obtained for Trento

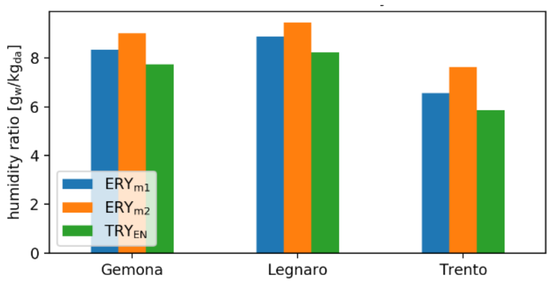

Fig. 4 – Annual mean air humidity ratio values for the reference years for the three considered locations

3.2 Simulation Results

Using the reference years to perform the heat and moisture transfer simulation of five wall build-ups made it possible to analyze the effect of the selection of the statistic on the moisture accumulation risk assessment. For each simulation, the presented results are those obtained after the dynamic equilibrium between the external conditions and the wall was reached (the initial conditions were similar to the moisture content distribution and the temperature distribution of the last timestep of the reference year).

The simulations of the concrete and timber single layer walls showed, for all three locations, higher moisture content values for most days of the year, for the ERY_{m1}, and the lowest for the TRY_{EN} weather files. As an example, the moisture contents of the concrete single layer are shown in Fig. 5 for the case of Gemona del Friuli. The other walls under examination showed more complex behaviors (see, for instance, the hollow brick wall in Fig. 6), although the annual average moisture contents (presented in Fig. 7) confirm that the TRY_{EN} simulations have the lowest annual mean moisture contents.

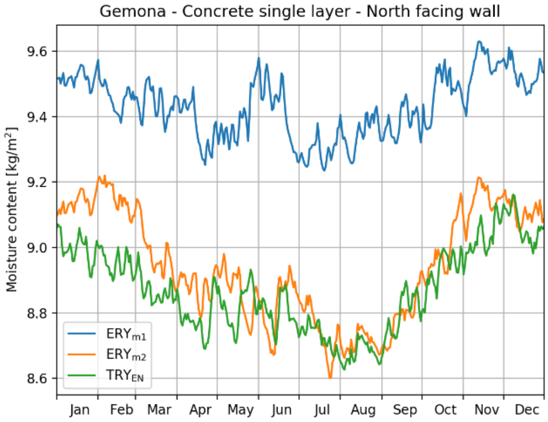

Fig. 5 – Daily average values of the moisture content of the concrete single layer facing North, for Gemona del Friuli

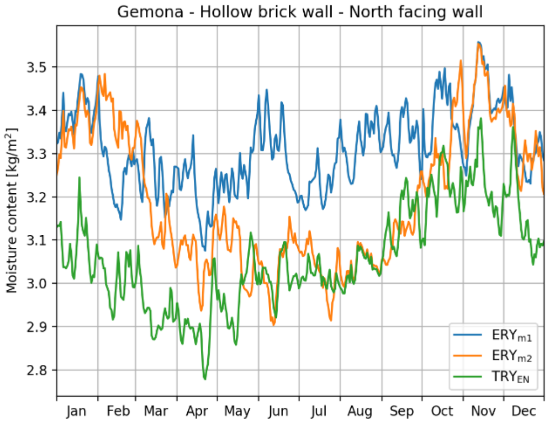

Fig. 6 – Daily average values of the moisture content of the hollow brick wall facing North, for Gemona del Friuli

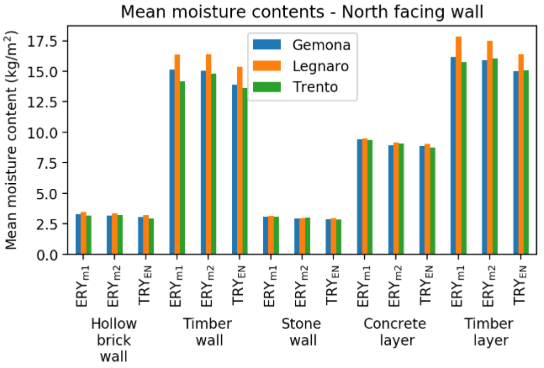

Fig. 7 – Annual mean total moisture contents of the five walls considered for the North orientation

Considering the wall build ups, the interstitial moisture accumulation risk was used as a parameter of comparison. For the sake of comparison, the interstitial moisture accumulation risk was calculated as the number of days in which the relative humidity was higher than the 80 % in the wall material, with the exception of the material layer exposed to the outside. Although Fig. 8 shows that the response of the walls to the external conditions was highly structure dependent, the ERY_{m1} and the ERY_{m2} provide higher risks than the TRY_{EN}. Similar results were obtained for the other orientations, with some exceptions such as the stone wall located in Gemona del Friuli. In this case, higher risks were found for the TRY_{EN}, even though the moisture content of the wall was lower than the ones obtained with ERY_{m1} and the ERY_{m2}. Potential differences in the behavior of different wall types should be expected, given that each wall has a different response to the same weather events and a weather event that is critical for the stone wall might not be critical for the hollow brick wall.

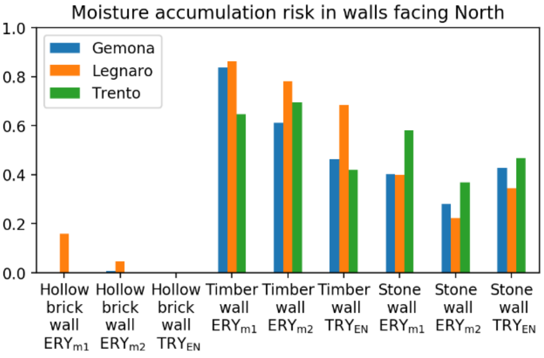

Fig. 8 – Moisture accumulation risk (fraction of days with relative humidity values over the 80 %) for the considered walls

Simulations were also performed to consider higher internal moisture loads. As shown in Fig. 9, the moisture contents were higher than in simulations with normal internal moisture loads and the relationship between the results of the three reference years was the same.

For Gemona del Friuli, the availability of the required weather data made it possible to run simulations which also included driving rain. In this case, the highest moisture contents were obtained using the ERY_{m2} (Fig. 10). A possible explanation for this effect could be that the months with extreme air humidity ratios are also the months with the highest rainfall intensity values and with the lowest drying potential.

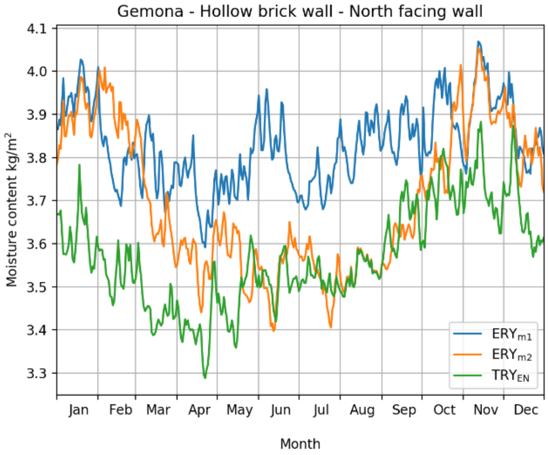

Fig. 9 – Moisture content of the hollow brick wall facing North, for Gemona del Friuli with high internal moisture loads

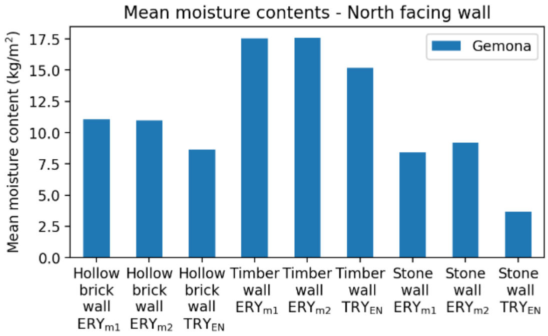

Fig. 10 – Annual mean moisture contents of the three considered walls facing North in Gemona del Friuli, considering driving rain

4. Conclusions

The comparison between typical and extreme weather files made it possible to confirm that the latter are more suitable for moisture accumulation risk analysis. This can be observed, in terms of larger moisture contents in the tested walls, and also in terms of risks of moisture accumulation. The use of extreme instead of typical conditions can allow for a more robust design of the opaque components and, consequently, longer durability and a higher thermal hygrometric performance. Nevertheless, even if the proposed approach represents an improvement on an approach based on EN ISO 15927-4:2005 reference years, some limitations remain and indicate opportunities for further advancements. In particular, further research is planned to combine rainfall and wind direction data to determine the risk of wet walls' surface and to evaluate the impact of such input in the extreme year definition and on the walls' thermal hygrometric performance.

In terms of further developments, for a safe application of risk analysis it is necessary to extend the evaluation of the extreme weather files to other building structures and materials.

Acknowledgement

The authors would like to thank ARPA Veneto, ARPA FVG (OSMER), and Fondazione Edmund Mach for supplying the raw weather data, and Bauklimatik Dresden Software GmbH for providing the software Delphin 6.

This research has been made possible thanks to PhD funding from the Provincia di Udine and has been partially funded by the project “Klimahouse and Energy Production” in the framework of the programmatic-financial agreement with the Autonomous Province of Bozen-Bolzano of Research Capacity Building.

Nomenclature

Symbols

p	General variable
m	Calendar month
y	Year of the Multi-year weather data record
i	Day of the year
$\underline{p}$	Daily mean of the values of the general variable p
$\Phi(p,m,i)$	Cumulative distribution function
$K(\underline{p},m,i)$	Ranking of the i^{th} day of the month m
$F(p,y,m,i)$	Cumulative distribution function within the calendar month m of the year y
$J(i)$	Ranking of the i^{th} day of the month m of the year y
$F_S(p,y,m)$	Finkelstein-Shafer statistic
d_{tot}	Total thickness of a wall
$S_{d,tot}$	Total equivalent air thickness of a wall (vapor permeability)
U_{tot}	Total thermal transmittance of a wall

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