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Climate data for moisture simulations

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Climate data for moisture simulations: producing a Danish moisture reference year and comparison with previously used reference year locations

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Abstract. Buildings comprise of complex systems, and various materials in combination. Different materials have different expected service life, and degradation processes start as soon as a building is put into operation. Degradation processes are often accelerated with the presence of moisture. To build robust and moisture safe buildings, hygrothermal simulations are used to predict hygrothermal conditions in constructions, and especially areas of risk. Simulations are useful tools for prediction of moisture accumulation, and results can further help predict the risk of moisture damage, i.e., frost damage or mould growth. The external climate can therefore have a significant impact on the service life of constructions. Due to the lack of a sufficient Danish climate reference year, including precipitation, hygrothermal simulations of Danish constructions are currently performed with either Danish climate data without precipitation (primarily for energy and indoor climate conditions), or with climate data from closest locations in either Sweden or Germany which include rain. Therefore, a complete Danish reference year, including precipitation, will inevitably enhance the value of hygrothermal simulations of buildings in Denmark. This paper presents the method used to develop full climate datasets based on Danish conditions, including precipitation. To integrate the climate datasets in the hygrothermal simulation programs, the climate datasets contain the following parameters: temperature, relative humidity, wind direction and speed, solar radiation, rain, as well as estimations for cloud cover and longwave radiation based on the other climate parameters. The climate datasets generated and presented in this paper, represent a Typical Meteorological Year (TMY), without extreme events, generated according to EN ISO 15927-4:2006. The climate datasets are based on Danish climate data from the period 2001-2019, provided by the Danish Meteorological Institute, DMI. By prioritizing climate parameters, and through statistical analysis, representative 1-year reference climate datasets were generated based on Danish climate conditions. The climate parameters of the 1-year reference climate datasets are compared with the traditionally used Swedish and German datasets, and a Danish Design Reference Year (DRY) from 1995.

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1. Introduction

A reference year must represent a climate that allows an appropriate evaluation of the moisture load a construction is exposed to. There are different types of reference years, prepared for different purposes, which differ in terms of which parameters are included and their extremes. There is however no standardized method for preparing reference years for hygrothermal simulations, and different approaches are used, including [1-4]. Vandemeulebroucke et al. [5] describes two general methods: (1) reference year developed based on climate data, which does not relate to constructions or degradation mechanisms, i.e., a general "one-fits all" reference year; (2) reference year developed based on degradation mechanisms for various constructions and materials. Furthermore, each type of reference year should be based on climate data from a sufficiently long period (10-30 years) and should be representative for the given location [6]. In this study, five general "one-fits all" moisture reference years were prepared through statistical analysis of the climate parameters, using different selection criteria. The five reference years were compared with Swedish and German reference years from nearby locations. The reference years were further evaluated by comparing the water vapour saturation deficit and the risk of mould growth using the VTT model [7], like the approach by Kalamees et al. [2].

2. Methods

2.1. Climate parameters - raw data collection

The climate datasets were supplied by the Danish Meteorological Institute (DMI) and covers the period 2001 until ultimo 2019. The general basis was the weather station Sjælsmark (6188) [temperature, relative humidity, wind speed, global radiation], supplemented with data from Hillerød SE (30180) [rainfall], Store Hareskov (30230) [rainfall] and Gørløse (30140) [rainfall]. Regarding rainfall, data for 2001-2009 were obtained from stations 30140, 30180, and 30230, while for 2011-2019 data were obtained from Sjælsmark station. There was a lack of reliable rainfall data from Sjælsmark as well as the nearby weather stations during 2010. The year of 2010 was therefore taken out of the following processing of the climate datasets, as the lack of rainfall data in 2010 could affect the statistical selection process. The same climate dataset from Sjælsmark (including 2010) was previously used to prepare reference years for energy and indoor climate simulation in computer programs required by the Danish building code.

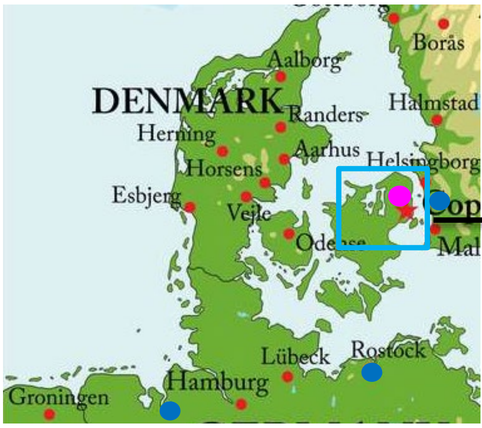

Figure 1. Main weather station 6188 (Sjælsmark) measures global radiation temperature, relative humidity, and wind (pink dot). Blue dots are the nearby German/Swedish stations. Source: Colourbox [8]

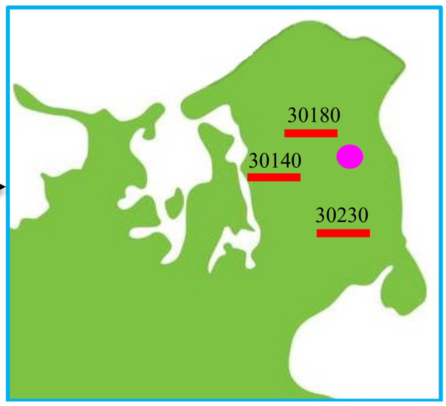

Figure 2. Weather stations for rainfall data marked with red lines. Pink dot show Sjælsmark station. Source: Colourbox [9]

2.2. Generation of moisture reference years

The Danish moisture reference years were generated using 18 years of data from DMI, 2001-2019, excluding 2010. The reference years were generated according to EN ISO 15927-4:2006 [6] sections 5.2 and 5.3, which is typically used for generating reference years for simulation of energy for heating and cooling of buildings. The standard describes how the most typical months are selected based on 3 primary and 1 secondary variables. The three primary variables and the secondary variable for selection of months for the five generated moisture reference years are shown in Table 1. Five reference years were generated to investigate which setup of primary and secondary variables resulted in the most suitable moisture reference year. The most suitable reference year will be used for the entire country, until further works are carried out using more regional climate data, which are not available currently.

Table 1. Selected criteria and remarks

#	Primary variable	Primary variable	Primary variable	Secondary variable	Remarks
1	Temperature	Relative humidity	Rainfall	Wind direction	
2	Temperature	Relative humidity	Rainfall	Radiation	Heavy construction
3	Temperature	Relative humidity	Radiation	Rainfall	Light construction
4	Rainfall	Wind direction	Wind speed	Radiation	Wind driven rain
5	Rainfall	Wind speed	Radiation	Temperature	Mix

The moisture reference years were pieced together from months chosen as the most representative for the average of the entire data period, based on the selected primary and secondary variables. The transitions between the selected months were carried out using interpolation to ensure a smooth transition, where the last 8 hours before and the first 8 hours after the transition were adjusted. A weighted average of each pair of measurements was used. The same process was done for the transition between December 31st and January 1st, to enable cyclic multi-year simulations to be performed. The moisture reference years were generated without data for February 29th. If the selected February month contained 29 days, the 29th was removed and transition was done between February 28th and March 1st. The reference years would therefore always contain 8760 hourly values.

Separation of global radiation into diffuse- and direct shortwave radiation was carried out using Python DIRINT function from the package pvlib [10]. The method for separating global radiation into diffuse- and direct radiation is described in [11-12].

2.3. Cloud cover and longwave radiation

The datasets obtained from DMI did not contain measurements for cloud cover or longwave radiation, which are needed for the hygrothermal simulations. Instead, a two-part method was used, which combined cloud cover estimated by the program BSim [13] using temperature, relative humidity and short-wave radiation data, and average hourly cloud cover values for each month of the year - obtained from U.S. Department of Energy [14]. This combination was used since the method BSim used for estimating cloud cover is suitable only for daytime (like the methods described in [15]), and therefore the average hourly cloud cover values were used for night-time.

Subsequently, the longwave radiation was estimated according to equations (1)-(2), in accordance with section 2.9.1.13 of EnergyPlus Auxiliary Programs Version 22.1.0 Documentation [16]. The longwave radiation or horizontal infrared radiation intensity is given by

$$Horizontal_{IR} = \varepsilon \sigma T_{drybulb}^4 \tag{1}$$

where $Horizontal_{IR}$ is the horizontal IR intensity [W/m^2], ε is the sky emissivity [-], σ is the Stefan-Boltzmann constant = 5.6697e-8 [W/(m^2·K^4)], and $T_{drybulb}$ is the drybulb temperature [K].

The sky emissivity is given by

$$\varepsilon = \left(0.787 + 0.764 ln\left(\frac{T_{dewpoint}}{273}\right)\right)(1 + 0.0224N - 0.0035N^2 + 0.00028N^3) \tag{2}$$

where $T_{dewpooint}$ is the dewpoint temperature [K], and N is the opaque sky cover [tenths].
The dewpoint temperature was calculated according to EN ISO 13788:2013 Annex E.1 [17].

2.4. Checking climate parameters in the generated moisture reference years
After generating the moisture reference years, distribution functions were plotted to ensure that the selected typical months did not appear too extreme. Subsequently, each climate parameter was visualised, to ensure that the reference years did not contain abnormally high/low values or other types of errors. In the case of missing data prior to selection of months, interpolation was performed between previous and subsequent values.

2.5. Comparison of the moisture reference years
Several different methods were applied to evaluate the five generated moisture reference years as described briefly in the following sub-sections. The moisture reference years were compared with the traditionally used German and Swedish datasets and with the 1995 Danish DRY dataset [18]. It should be noted that only daily or monthly mean values were available in the 1995 DRY dataset.

2.6. Absolute difference between climate parameters. Aside from presenting the individual climate parameters in graphical format, the absolute (ABS) difference was determined between the generated moisture reference years and the reference years from Lund (Sweden), Bremerhaven and Rostock (Germany). Lund and Rostock data were obtained from WUFI Pro version 6.6, while Bremerhaven data were obtained from Delphin version 6.1.4. The ABS difference was calculated based on the hourly values for each climate parameter, and the average ABS difference was then determined for each parameter in each moisture reference year relative to Lund, Bremerhaven, and Rostock respectively.

2.7. Water vapour condensation analysis. Another method used to compare the moisture reference years considers the water vapour saturation deficit, introduced by Kalamees & Vinha [2]. Briefly explained, the difference between saturation and ambient absolute humidity of the outdoor air ($\Delta v_{sat.def}$) [g/m^3] is determined. $\Delta v_{sat.def}$ is determined for the months December to February, where the risk of condensation is most critical. $\Delta v_{sat.def}$ gives an indication of the drying potential for constructions exposed to the given climate conditions, where higher $\Delta v_{sat.def}$ values indicate a better drying potential.

2.8. VTT mould growth modelling. In addition to evaluating the differences between the individual climate parameters, the theoretical risk of mould growth was evaluated using the VTT mould growth model [7]. The output of the model is the mould index (M), ranging from 0 to 6, where 0 corresponds no growth and 6 to heavy growth (100% coverage). Values 3–6 are growth within the visual range. The model was used to evaluate the combination of temperature and relative humidity over time. In this study, the risk of mould growth was modelled assuming a wooden beam exposed to the climatic conditions of the generated moisture reference years and the reference years from Lund, Bremerhaven, and Rostock. The risk modelling was carried out assuming a material sensitivity of “very sensitive” with a decline factor set to “wood recession”, corresponding to untreated wood. The modelling was carried out using 4 years of simulation data, i.e., the reference years were cycled 4 times. Finally, ABS differences were determined for the VTT results.

3. Results and discussion

In selecting the most suitable reference year for Denmark, it was important to determine how much the five new reference years differed from the nearby German and Swedish climate stations, as it was estimated that the Danish climate could be somewhere in between in terms of temperature, while most of the other parameters were expected to be rather similar to Lund, due to the close proximity. For this, the individual climate parameters were compared to the data from the nearby German and Swedish climate stations, and the risk of condensation and mould growth were evaluated. Comparison with the

1995 DRY dataset was carried out only for the climate parameters, as the data were not suitable for comparison of ABS difference, condensation risk and mould growth risk.

3.1. Climate parameters - comparison

Figure 3 shows that the Danish reference years are all similar to the German/Swedish reference years in terms of monthly average temperature. However, slightly lower temperatures were observed during January and February. Slightly higher temperatures were generally observed when compared with the 1995 DRY dataset. For the relative humidity, the levels are also similar, but from July to December higher relative humidity was observed for all the Danish reference years compared with the German/Swedish reference years. The five new Danish reference years were all generally similar to the 1995 DRY dataset. Furthermore, the yearly average relative humidity was merely 1-2.5 %-points higher for the Danish reference years compared with the German/Swedish reference years and within ±1 %-point compared with the 1995 DRY dataset.

In terms of the impact of wind and rain, a comparison is presented for the total amount of wind driven rain in relation to orientations for the 8 reference years, generated by WUFI® Pro (Figure 4). This was not done for the 1995 DRY dataset, due to the data format and lack of certain data. The underlaying parameters making up the wind driven rain load (wind speed, wind direction, and horizontal rain), are available in the supplementary data [19]. Figure 4 shows that the 5 new Danish reference years and the German/Swedish reference years all have the range between south and west as the prevailing directions for wind driven rain, and that all the Danish reference years have lower amounts of wind driven rain compared with Lund, Bremerhaven and Rostock. The Danish reference years seem to best match Rostock in terms of wind driven rain, except that Rostock has more rain load from the western to northern directions. In terms of wind direction, Bremerhaven seemed to best match the Danish reference years, but Bremerhaven had considerably higher rain load. The comparison indicates that Lund, Bremerhaven, and Rostock could likely be more severe in terms of use in hygrothermal simulations. Table 2 shows the monthly and annual horizontal rain load. Compared with the 1995 Dry dataset, the 5 new Danish reference years had from 14% lower (Ref #4) to 11% higher (Ref #1) annual rain load. On a month-to-month basis, the new Danish reference years generally had higher rain load in February, March and August, while lower rain load was generally seen in June and December.

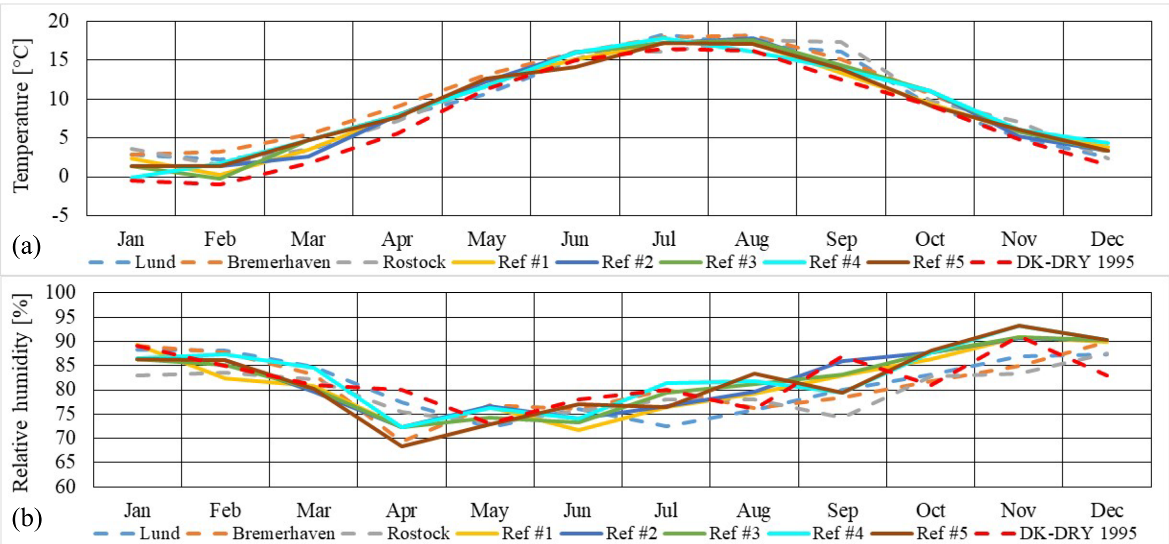

Figure 3. Monthly average values for the reference years: (a) temperature; (b) relative humidity.

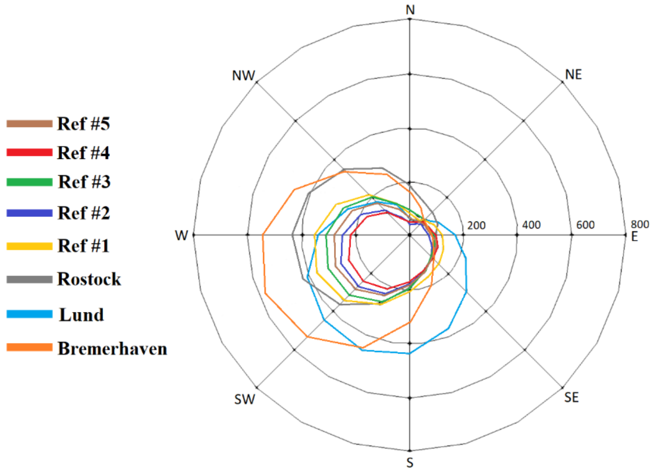

Figure 4. Total amount of wind driven rain in relation to orientation. Produced in WUFI® Pro.

Table 2. Monthly and annual horizontal rain [mm]

	Lund	Bremerhaven	Rostock	Ref #1	Ref #2	Ref #3	Ref #4	Ref #5	DK-DRY 1995
Janary	51	41	38	57	53	53	59	53	60
February	59	27	0	47	53	44	34	53	18
March	84	38	35	52	30	49	43	49	20
April	63	34	16	29	30	30	29	11	40
May	56	61	80	75	75	62	61	28	52
June	88	54	55	34	31	88	31	73	101
July	40	104	68	88	88	88	49	89	89
August	111	40	127	112	53	87	70	74	35
September	45	55	49	93	60	31	60	61	64
October	56	81	49	88	70	71	70	102	86
November	25	82	49	65	49	65	59	59	66
December	140	59	71	54	55	56	51	56	83
Annual total	818	677	637	793	648	724	617	708	714

Regarding direct and diffuse radiation (Figure 5), the Danish reference years are similar to Lund and Rostock, and the 1995 DRY dataset. For Bremerhaven, there were considerable differences to all the other reference years, i.e., lower direct and higher diffuse radiation. The reason for these differences is unclear. Regarding the longwave radiation, the 5 new Danish reference years, the 1995 DRY dataset and Lund (where radiation values were estimated from cloud cover), had lower monthly average values compared to Bremerhaven and Rostock. Furthermore, boxplots generated to visualise the data distribution (see [19]), showed considerable differences between the Danish reference years and Lund (both with estimated longwave radiation by cloud cover), and the German reference years (measured radiation).

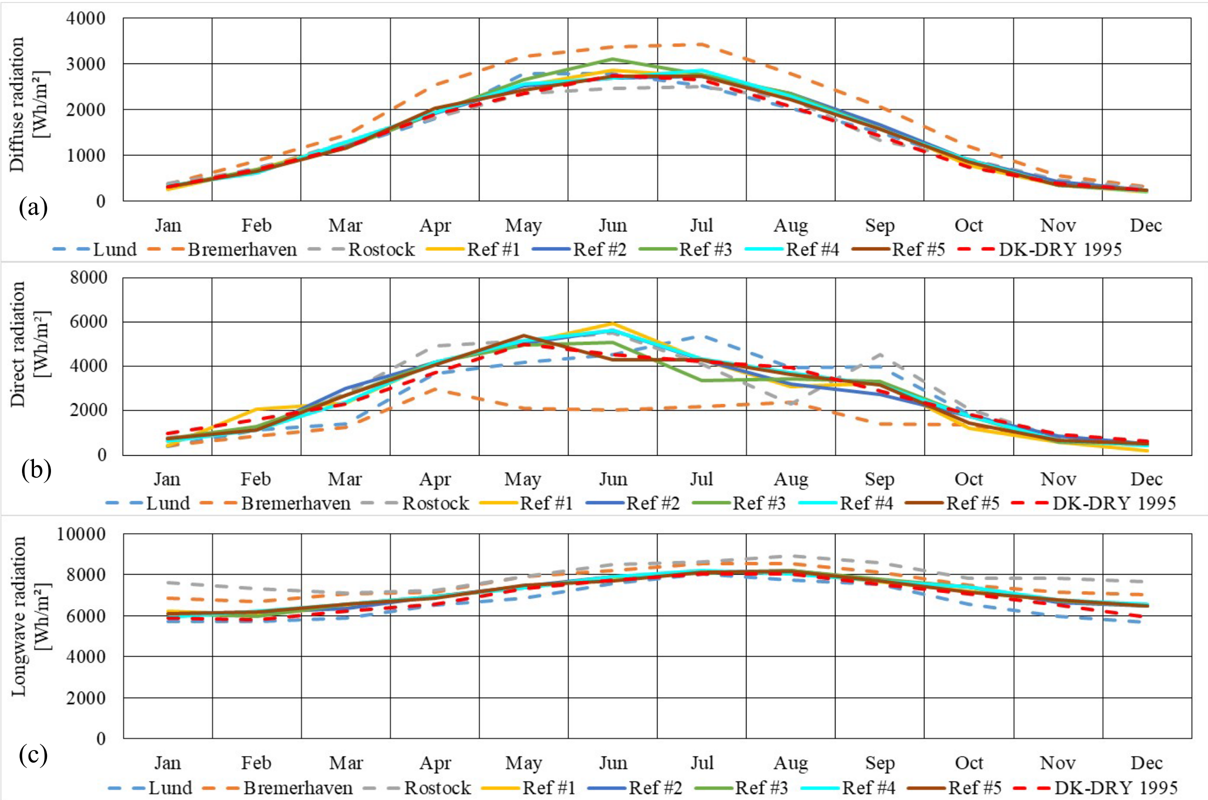

Figure 5. Monthly average for total daily values for the reference years: (a) direct normal radiation; (b) diffuse horizontal radiation; (c) Longwave radiation.

3.2. ABS difference between the new Danish reference years and the German/Swedish reference years

Table 3 shows the average hourly ABS differences between the Danish, German, and Swedish reference years for each of the climate parameters. The average ABS differences for the three locations and each of the climate parameters were summarized. It was observed that reference year #2 had the best match for most of the climate parameters, however, the differences between the Danish reference years were rather small (generally within 2-5%).

Table 3. Average hourly ABS difference between reference years. Small values indicate better match between the reference years.

	Lund					Bremerhaven					Rostock				
	Ref #1	Ref #2	Ref #3	Ref #4	Ref #5	Ref #1	Ref #2	Ref #3	Ref #4	Ref #5	Ref #1	Ref #2	Ref #3	Ref #4	Ref #5
Temperature [°C]	3.6	3.3	3.4	3.4	3.5	3.5	3.5	3.5	3.4	3.7	3.7	3.2	3.5	3.4	3.3
Relative humidity [%]	11	10.8	11.2	11.1	11	12.4	12.2	12.5	12.4	12.3	12.5	12.2	12.4	11.9	12
Wind speed [m/s]	2.1	2.1	2.1	2	2	2.9	2.8	2.9	2.8	2.8	3.1	3.1	3	3	3
Horizontal rain [mm/h]	0.17	0.15	0.16	0.15	0.16	0.15	0.14	0.15	0.14	0.15	0.15	0.14	0.15	0.14	0.15
Directe radiation [W/m²]	128	126	122	127	118	111	110	106	110	105	126	122	120	119	123
Diffuse radiation [W/m²]	29	29	29	29	29	29	28	27	29	28	28	27	28	27	28
Longwave radiation [W/m²]	31	30	31	32	31	30	30	30	29	31	43	42	43	42	42

Green highlights illustrate best match.

3.3. Water vapour condensation analysis – December to February

In terms of the risk of condensation, determined by the difference between saturation and ambient absolute humidity of the outdoor air ($\Delta v_{sat.def}$), the Danish reference years were rather similar around

$\Delta v_{sat.def}$ = 0.7 g/m^3 and very similar to the saturation deficits found for Lund and Bremerhaven (Table 4). Meanwhile, Rostock was slightly higher at 0.91 g/m^3. In addition, the saturation deficits were accumulated over the 3-months period, in which case the differences between the Danish reference years and Lund, Bremerhaven and Rostock were 0.9 to 5.8%, -3 to 2.1% and 22.2 to 26.1% respectively. This indicated that over the winter period, Rostock had a considerably higher accumulated $\Delta v_{sat.def}$ and therefore a lower risk of condensation compared with the Danish reference years, Lund, and Bremerhaven.

Table 4. Comparison of saturation deficits, $\Delta v_{sat.def}$ [g/m^3], for the period December to February

	Lund	Bremerhaven	Rostock	Ref #1	Ref #2	Ref #3	Ref #4	Ref #5
Average $\Delta v_{sat.def}$	0.71	0.69	0.91	0.71	0.69	0.68	0.67	0.69
Accumulated $\Delta v_{sat.def}$	1540	1481	1961	1526	1485	1470	1450	1486

3.4. Mould growth risk

For the theoretical risk of mould growth with the VTT model (Figure 6 and Table 5), there were considerable differences between the Danish reference years and Lund and Rostock, while the results were closer to the predicted mould risk for Bremerhaven. The model indicated limited to no risk for Lund and Rostock, and a high risk for the Danish reference years and Bremerhaven. A comparison between the absolute differences shows that reference year #1 and #2 generally were most similar to the German and Swedish reference years in terms of mould growth risk.

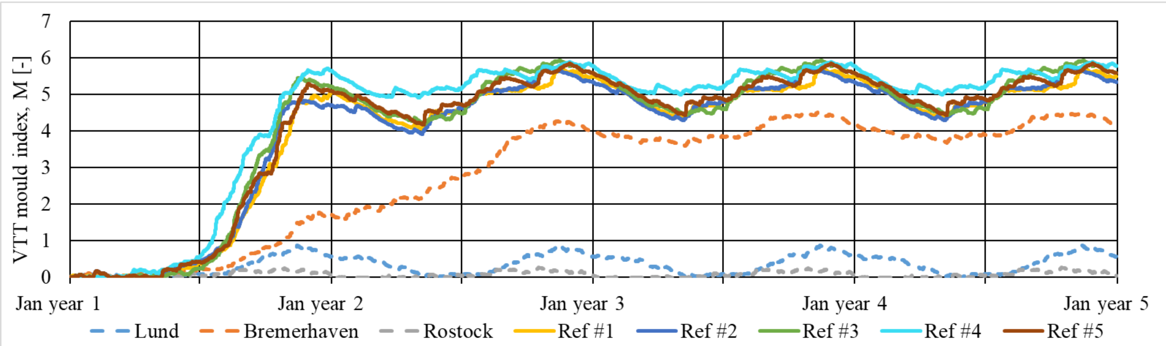

Figure 6. VTT mould growth predictions for wood exposed to the climatic conditions of the generated moisture reference years, and comparison with Lund, Bremerhaven, and Rostock.

Table 5. Average ABS hourly difference between new Danish reference years and German/Swedish reference years for the VTT results. Small values indicate better match between the reference years.

		Ref #1	Ref #2	Ref #3	Ref #4	Ref #5
Average ABS hourly difference for VTT results	Lund	3.74	3.76	3.92	4.21	3.89
	Bremerhaven	1.22	1.24	1.41	1.69	1.37
	Rostock	4.01	4.03	4.19	4.48	4.16
Sum of ABS difference for VTT		8.97	9.03	9.52	10.38	9.42
SD for ABS hourly difference for VTT results	Lund	1.67	1.65	1.73	1.72	1.71
	Bremerhaven	0.81	0.81	0.93	1.00	0.85
	Rostock	1.79	1.77	1.85	1.83	1.82

Green highlights illustrate best match with the given German/Swedish reference year, while blue highlight illustrates best overall match.

4. Conclusion

This paper presented the prepared Danish reference years, which were compared with reference years from nearby German and Swedish climate stations, and the Danish 1995 DRY dataset. The results showed that the Danish reference years were relatively similar to the German and Swedish reference years and the Danish 1995 DRY dataset for most of the climate parameters, often with the Danish reference years lying in between the German and Swedish. However, considerable differences were noted for the wind driven rain load, where the German and Swedish reference years were found to be more severe than the Danish. Moreover, the results indicate that the method used to estimate longwave radiation from cloud cover tends to underestimate the values. While the German and Swedish reference years had higher wind driven rain load, the mould results indicate that the temperature and relative humidity conditions are more severe in the Danish reference years. This correlates with the water vapour saturation deficit calculations, which generally indicated higher risk of condensation in the Danish reference years. An overall comparison between the five Danish reference years indicated that reference year #2 had the best match with the German and Swedish reference years for the climate parameters, while reference year #1 had the best match for the mould results. However, the differences between reference year #1 and #2 were quite small and both reference years could be a good candidate as a new Danish moisture reference year. Further testing with hygrothermal simulation is needed.

5. Acknowledgements

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