Hygrothermal and Mold Modeling of Building Envelopes Under Future Climate Conditions

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ABSTRACT: Climate-responsive design now includes design for future climate, which involves design for gradually changing climate conditions. Here we examine the importance of an overlooked aspect of climate-adaptive design: the susceptibility of residential lightweight timber construction to mold growth in future climate conditions. This paper seeks to understand the hygrothermal performance of newly built, code-compliant residential building envelopes under future climate conditions across U.S. climate zones. Combined hygrothermal and mold modeling is performed on a typical, code-compliant exterior residential wall assembly, using morphed future climate data in representative cities in three climate zones. The results suggest widespread mold issues under future climate conditions. Mold risk was identified in each of the three climate zones tested (ASHRAE climate zones 4A, 5A, and 6A). Mold issues emerge as early as the mid-21st century for climate zones 4A and 5A. These findings suggest the need for the consideration of climate adaptation and resilience in the development of building codes.
KEYWORDS: Hygrothermal simulation, mold growth modeling, health, climate adaptation, resilience

1. INTRODUCTION

Our climate is warming, historically defined climate zones are shifting, extreme weather events are increasingly frequent and severe, and these changes affect the thermal and hygrothermal performance of our buildings. The scope of climate-responsive design now includes design for future climate, which means design for gradually changing and increasingly severe climatic conditions [1]. Urban areas across the United States (U.S.) are expected to become warmer due to climate change [2], with North American populations living in temperate climates expected to suffer from an increase in the frequency and severity of extreme heat events [3]. While our codes and regulations remain largely based on historical data [1], our approach to the design of buildings, including envelope design, will need to evolve as the climate warms [4,5].

Wall cavity surfaces vulnerable to condensation can facilitate the conditions necessary for mold growth [5,6]. The geographical locations and types of cavity constructions that are most vulnerable will change as our climate warms [5]. Molds grow everywhere there are nutrients and biologically available moisture. Building materials are included among the many potential substrates for mold growth. Wall cavities in moisture-damaged homes can become a virtually unlimited feedstock upon which fungal growth can be established. To avoid mold growth, building design must meet the needs of the regional climatic conditions. “Imported” design strategies do not perform well in new climates [6]. Though limited, studies show that buildings will face greater risk of rot-decay damage if located in one of the many climates that will experience warmer, wetter weather [5].

Mold growth in wall cavities causes moisture-induced decay, which, under certain conditions, can negatively affect structural integrity over time. Such decay problems in buildings are most often the result of moisture damage, which can result from water leakage, convection of damp air and moisture condensation, and structural moisture accumulation. High wood moisture content and persistent high humidity exposure pose high risks for bio-deterioration of unprotected timber [7]. Damage due to biological action is the main mechanism that affects wood durability in building structures [8]. It is estimated that approximately 90% of damage in residential wood buildings is the result of temperature and moisture effects [9].

Furthermore, mold growth has adverse effects on indoor air quality. Occupants may be exposed to mold growth in wall cavities, and such exposures can have health implications. Numerous studies have shown that water-damaged homes are associated with adverse respiratory effects [10-12]. Though mechanisms and processes for fungal spores to move through building envelopes are complex [13], one source of microbial exposure may be attributed to the migration of spores through penetrations in wall constructions [14]. Additionally, asthma severity can be affected by microbial exposures: exposure to allergenic fungi in homes has been associated with a

36-48% exacerbation of current asthma symptoms [15].

Given this context, this paper seeks to understand the hygrothermal performance of newly built, code-compliant residential building envelopes under future climate conditions across U.S. climate zones. The results of this study may help practitioners understand retrofit needs and approaches as our climate changes, as well as effects of climate change on anticipated building service lives. This study poses the following hypotheses: (1) Certain climate zones are at higher risk than others for mold growth in wall constructions; (2) Wall constructions that perform well under historic conditions will show mold growth under future conditions.

2. METHODOLOGY

This methodology, which expands on past work [20], involves a three-step process. First, a morphing process is used to convert typical meteorological year (TMY) weather files to future weather files. Second, a hygrothermal simulation is performed on an exterior wall assembly in WUFI Pro 6. Third, simulated temperature and moisture data from the hygrothermal model are used to simulate mold growth potential using the VTT model [16-18]. The resulting 10-year mold index time series is used to evaluate how climate affects mold growth.

2.1 Future Weather Files and Climate Selection

As outlined above, the first step in this study is to morph a TMY weather file to future conditions. The Weather File Module of the WeatherShift™ tool [19] is used to perform the morphing procedure. TMY files are composed of twelve "typical" months that comprise a "typical" year. These are derived from historical weather data using statistics. The WeatherShift™ tool takes the TMY data as an input and "morphs" each variable, using several relatively simple transformations. Because they are based on historical data, the morphed data are meteorologically realistic. However, because most of the transformations preserve historical variability, the morphed data may understate changes in future extremes [19].

The morphing technique transforms historical time series data based on projected changes in the monthly averages of several climatic variables. Future values of these variables are uncertain, particularly at local scales; thus, the offset values are calculated for a group of climate predictions that are generated from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The CMIP5 models are run for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Representative Concentration Pathways (RCPs). Offsets are calculated for several future time periods (2026-2045, 2056-2075, and 2080-2099) for both the 4.5 and 8.5 RCPs. A cumulative frequency distribution (CFD) of the offset in mean monthly temperature is constructed for each combination of time period and RCP. It is based on the percentile rankings of the projections within the initial group of climate predictions [19]. This study uses the RCP 8.5 scenario and several different percentiles.

Table 1: Case study cities

City [Code reference]	ASHRAE Climate Zone	Predominant Exterior façade for new construction [27]	Code-required R-Value $(m^2 \cdot K)/W$ $[h \cdot ft^2 \cdot F / BTU]$	Vapor retarder	Continuous air barrier
Baltimore [2015 IECC]	4A	Vinyl	3.5 or 2.3 + 0.9 continuous [20 or 13 + 5 continuous]	Code-required	Code-required
Raleigh [2015 IECC*]	4A	Vinyl	2.6 or 2.3 + 0.4 continuous [15 or 13 + 2.5 continuous]	Code-required	Code-required
Boston [2015 IECC]	5A	Vinyl	3.5 or 2.3 + 0.9 continuous [20 or 13 + 5 continuous]	Code-required	Code-required
Chicago [2019 Chicago Bldg. Code]	5A	Vinyl	3.5 or 2.3 + 0. 9 continuous [20 or 13 + 5 continuous]	Code-required	Code-required
Columbus [2019 Res. Code]	5A	Vinyl	3.5 or 2.3 + 0.9 continuous [20 or 13 + 5 continuous]	Code-required	Code-required
Omaha [IBC 2018*]	5A	Vinyl	3.5 or 2.3 + 0.9 continuous [20 or 13 + 5 contniuous]	Code-required	Code-required
Milwaukee [WI Uniform Dwelling Code]	6A	Vinyl	3.5 or 2.3 + 0.9 continuous [20 or 13 + 5 continuous]	Code-required	Code-required
Minneapolis [IECC 2012*]	6A	Vinyl	3.5 or 2.3 + 0.9 continuous [20 or 13 + 5 continuous]	Code-required	Code-required

* Plus amendments

While the WeatherShift™ tool is able to morph most TMY variables, rainfall data are not projected. These data are crucial for hygrothermal simulation [20]. Therefore, rainfall data were manually extracted from the historical dataset and added, unchanged, to the projected dataset via Excel. This is a conservative approach.

Cities from ASHRAE climate zones 4A, 5A, and 6A [21] were selected for this study, as they are mixed-humid climates that will see increased temperature and absolute humidity [22-25]. Average monthly temperatures for cities in each of the three selected climate zones are shown in Figure 1. Selected cities and their corresponding 2020 code requirements are shown in Table 1. These code requirements were used to develop a standard test wall assembly for each city.

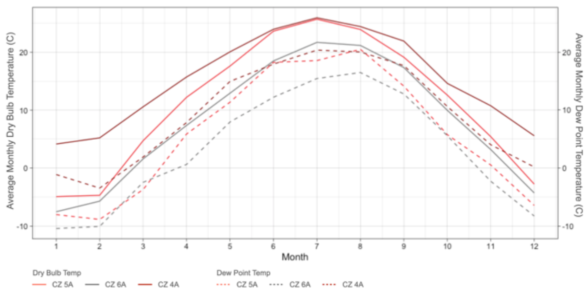

Figure 1: Average monthly temperatures for representative cities in each of the three climate zones (4A, 5A, and 6A).

2.2 Hygrothermal Model

The second step uses hygrothermal simulation to understand heat and moisture transport through each assembly. The dynamic hygrothermal simulation software package WUFI Pro 6 is used to perform this simulation. This model is well validated [27-28].

The program considers three groups of parameters: the component, including the envelope assembly, orientation, surface transfer coefficient, and initial conditions; the control, including the calculation period and related parameters; and the boundary conditions, including hourly indoor and outdoor temperature and relative humidity.

Hygrothermal outputs from WUFI were used to assess temperature and moisture changes at various points within the wall section.

As shown in Figure 2, the wall section includes fiberglass insulation between standard Douglas Fir studs. The total thickness of the wall is 17.4 cm, with a U-value of 0.22 W/m2K (R-Value of 24 ft^2ºF h/Btu). Table 2 provides properties for each material. A north orientation was used for the wall, and the initial condition of the assembly is 80% relative humidity and an initial temperature of 20ºC. These initial conditions are consistent with previous studies [20].

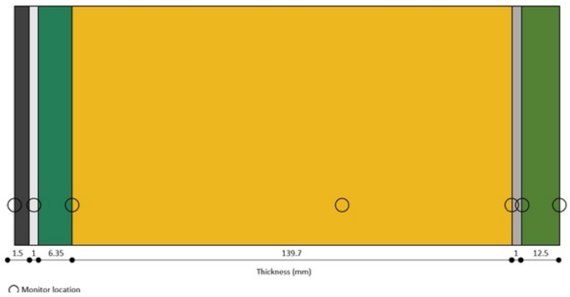

Figure 2: Wall section, including the following materials from left (exterior) to right (interior): vinyl siding (1.5mm), air barrier (1mm), oriented strand board (6.35mm), fiberglass batt insulation (139.7mm), 1-perm vapor retarder (1mm), gypsum board (12.5mm).

Table 2: Materials Data

Material	Thermal Conductivity [W/mK]	Density [kg/m³]	Specific Heat [J/kgK]
Vinyl siding	0.1696	829.0	2300
Air barrier	0.047	1.298	999.8
Polyolefin membrane	2.3	65	1500
Oriented Strand Board	0.084	575.1	1879.9
Fiberglass batt	0.035	19.22	841.5
Vapor retarder	2.3	130	2300
Gypsum board	0.163	850.6	870.9

Ten-year hygrothermal simulations were run in WUFI Pro, to confirm the equilibrium mold growth condition. The indoor climate follows ASHRAE 160 standards [29], such that indoor conditions were maintained between 21.1ºC and 23.9ºC via mechanical heating and cooling. Indoor moisture gains were specified at 0.000105 kg/s, and the maximum indoor relative humidity is capped at 50%.

2.3 Mold Model

The third step is to simulate mold growth. The VTT model [16] was used to simulate mold growth based on hygrothermal data from WUFI Pro. This model is derived from experimental studies on pine sapwood and spruce, and it was later expanded to include other building materials [30]. The simulation accounts for mold growth and decay based on dry-bulb temperature, relative humidity, and the material's sensitivity to mold growth. Model validation and details have been published widely [30-32]. The model calculates mold index (MI) hourly. The MI ranges from zero, which represents no growth, to six, which represents 100% surface coverage. The MI levels are shown in Table 3.

Table 3: The VTT Mold Index [17]

MI	Description
0	No growth.
1	Some growth detected only with microscopy.
2	Moderate growth detected with microscopy
3	Some growth detected visually.
4	Visually detected coverage >10%.
5	Visually detected coverage >50%.
6	Visually detected coverage 100%.

Mold growth calculations are performed in WUFI Mold Index VTT 2.0, which uses temperature and relative humidity outputs from WUFI Pro. Conditions are assessed at various points within the wall, with the interior face of the insulation cavity showing the highest potential for growth. Based on this, mold growth modeling is performed for the interior face of the insulation cavity, at the timber framing.

Lightweight timber residential walls in the US are typically framed with Douglas Fir, which is included in the VTT classification of "pine sapwood". The default sensitivity and specifications of pine are therefore used for subsequent mold index simulations.

3. RESULTS

Figures 3 and 4 show the results of the mold simulations. Figure 3 shows a 10-year time series for each city under different warming percentiles from the Weathershift™ cumulative frequency distributions; TMY3, 50th percentile 2080-2099, and 95th percentile 2080-2099 scenarios are shown.

In contrast, Figure 4 shows the equilibrium mold indices, which are extracted from the end of the ten-year simulations in Figure 3, at different periods of time and under different warming percentiles.

3.1 Impacted Climate Zones

As shown in Figure 3, the performance of the interior of the insulation cavity is as expected, i.e. no sustained mold growth, when using present-day weather data. A low MI (corresponding to minor mold growth detectable only with microscopy [16]) occurs only seasonally, which is considered acceptable [32].

The results change when modeling with morphed weather data. Under the highest warming scenario (95th percentile), an MI above 3, which corresponds to visible mold, is observed in every climate zone and in every city except Minneapolis. This result occurs because moisture from the warm, humid outdoor air builds up within the envelope. The higher temperature difference between the outdoor air and the cool interior air leads to moisture accumulation.

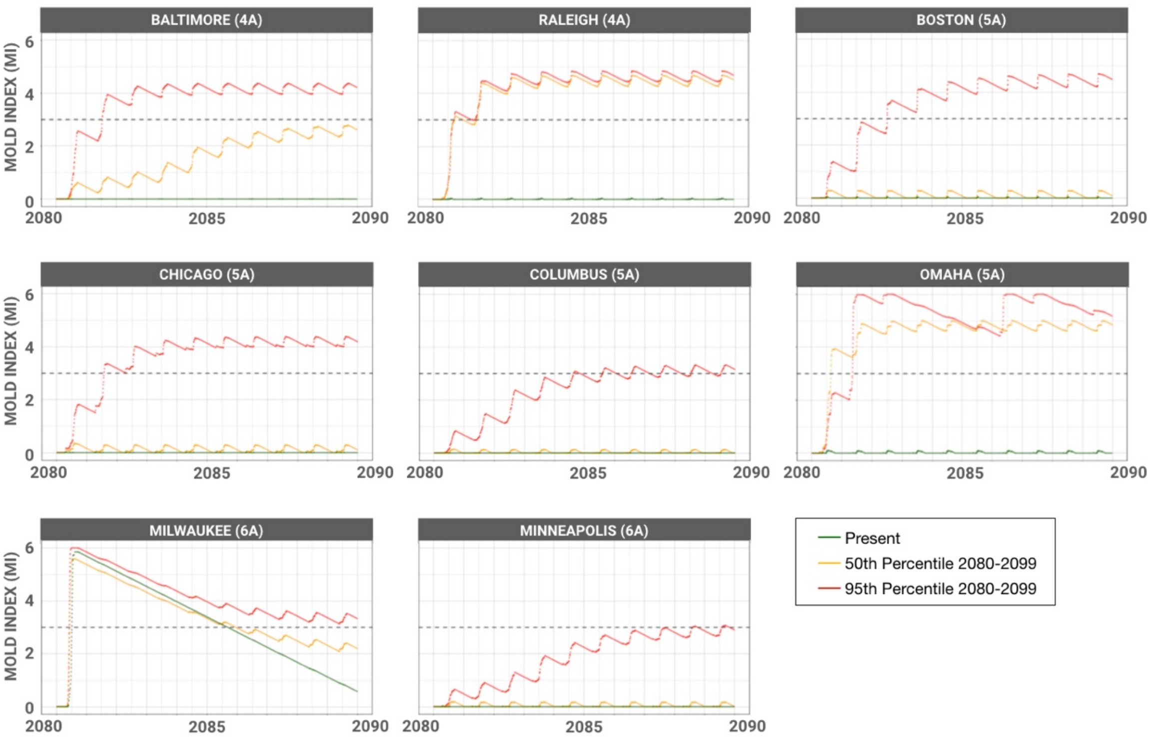

Figure 3: 10-year time series Mold Index for each case study city under different warming percentiles drawn from the Weathershift™ cumulative frequency distributions.

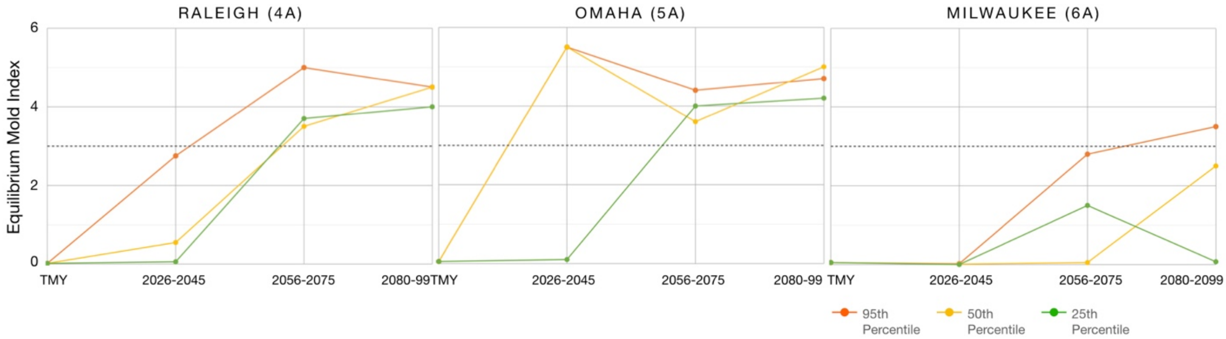

Figure 4: Equilibrium mold indices during different periods of time and under different warming percentiles.

The variability within climate zones is likely observed for two reasons. First, the nature of the rain data strongly affects the hygrothermal and mold modeling outputs [20]. This may explain the observed differences within climate zones, such as the difference between Boston and Columbus, which are both in climate zone 5A. Second, the assumed initial conditions strongly affect the early MI calculations. The initial conditions were assumed to have an 80% relative humidity and 20ºC temperature; however, these assumptions may be incorrect, and the conditions need to self-correct over time. This is why Milwaukee appears to have significant mold growth in the first few months/years of simulation, while arriving at a different equilibrium MI after ten years. This is an artifact of the initial assumptions.

2.4 Predicted Onset

Figure 4 shows the predicted onset of mold growth for three representative cities. Equilibrium MI represents the average MI at the end of the ten-year simulation. As Figure 4 shows, visible mold issues begin in the mid-21st century for both climate zones 4A and 5A, regardless which warming percentile is used. Climate zone 6A does not become sufficiently warm until 2080-2099, and even then, the projected MI is less than those predicted for climate zones 4A and 5A.

The results of this analysis also suggest the significant variability among the different warming percentile scenarios generated by Weathershift^{TM}. This is shown in both Figure 3 and Figure 4.

4. DISCUSSION

This study confirms the first hypothesis, which stated that certain climate zones are at higher risk than others for mold growth in wall constructions in changing climates. The study indicates that climate zones 4A and 5A are particularly vulnerable to significant mold growth in the building envelope type tested, while 6A is less vulnerable. We predict that dry (climate type B) and marine (climate type C) climates will not have mold risks, even in future climate conditions, as walls in these climate types will have the opportunity to dry, unlike climate type A (humid). Further work is needed to confirm these predictions.

This study also confirms the second hypothesis, which predicted that wall constructions that perform well under historic conditions will show mold growth under future conditions.

The future hygrothermal and mold problems observed in this study are sustained and extreme versions of what already occurs during the summer in mixed-humid climates. In these mixed climates, vapor barriers are placed on the interior (warm side) of the exterior wall construction to prevent warm, humid air from reaching the insulation layer during the winter. This approach is ill-suited for summer, when hot, humid air is instead on the exterior of the envelope, and migrates inward, into the cool wall assembly (assuming air conditioning). Sometimes this results in condensation in the wall, but these events are sufficiently brief and infrequent that sustained mold growth is not an issue, as observed in the analysis of present-day data in this study. However, when summer conditions become more frequent, sustained, and extreme, as they will in the future, the suboptimal envelope design provides adequate conditions for sustained mold growth, as we have observed here.

4.1 Future Work

This and previous studies [20] show the sensitivity of the analysis to climate data. Further work is needed to identify the sensitivity of the results to specific climate inputs and to develop more accurate ways of morphing currently missing parameters (i.e., rain).

Further research is also needed to understand the sensitivity of the hygrothermal and mold analysis to other parameters in the model, such as indoor climate conditions (i.e., building operations), construction parameters (e.g., choice of materials and insulation levels), and other numerical parameters of the simulations.

Additionally, while this research has identified future susceptibility to sustained mold growth, the scale of the problem has not been quantified, nor have mitigation techniques been identified and assessed. Each of these questions remain for future work.

5. CONCLUSION

This study demonstrates that lightweight timber building envelopes constructed to today's code requirements are not well-adapted for future conditions across several climate zones. This finding implicates a large number of single-family residential dwellings in the U.S and suggests the need for the consideration of climate adaptation and resilience in the development of building codes.

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