

Article

Climate-Dependent Effects of Environmental Longwave Radiation on the Hygrothermal Performance and Mold Risk of Building Envelopes

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Abstract

Environmental longwave radiation (ELR) can alter exterior-surface temperature and thereby modify moisture transport in building envelopes, yet its coupled hygrothermal effects are often simplified and remain insufficiently quantified across different climates. A transient coupled heat and moisture transfer (HAMT) model was developed using temperature and capillary pressure as the primary variables, with wind-driven rain (WDR), solar shortwave radiation, and dynamic sky longwave radiation incorporated into the exterior boundary. Validation against the HAMSTAD benchmark and long-term field measurements demonstrated that the model reproduces both near-saturated moisture behavior and the dominant transient hygrothermal response of multilayer walls. The capillary-pressure formulation was therefore adopted for subsequent ELR analyses in Harbin and Guangzhou, representing severe-cold and hot-summer/warm-winter climates in China, respectively. In Harbin, ELR-induced radiative cooling increased mean exterior-surface relative humidity by 9.1 percentage points and raised its peak from 91.4% to 99.7%; annual sensible and latent heat transfer increased by 7.88% and 3.33%, respectively. In Guangzhou, transient surface responses were much weaker, yet annual sensible heat transfer decreased by 11.99% while latent heat transfer increased by 7.54%, indicating a climate-dependent redistribution of heat and moisture transport. The maximum exterior-surface mold index increased from 2.20 to 3.89 in Harbin and from 3.69 to 4.27 in Guangzhou. These results identify a coupled pathway through which ELR-induced radiative cooling modifies surface humidity, internal moisture redistribution, energy partitioning, and long-term mold risk. Explicit representation of dynamic ELR is therefore important for climate-specific assessments of envelope hygrothermal performance and moisture durability.

Keywords: building envelope; heat and moisture transfer; environmental longwave radiation; capillary pressure; mold growth risk

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1. Introduction

Global climate change and increasing building-energy demand have intensified concerns about the energy efficiency, durability, and moisture safety of building envelopes [1,2]. Exterior walls are the principal interface for heat and moisture exchange between indoor and outdoor environments. Their long-term hygrothermal performance is governed by dynamic temperature, humidity, solar radiation, wind and rainfall

boundaries [3,4]. In porous building materials, sensible heat transfer, water-vapor diffusion, capillary liquid transport, evaporation and condensation occur simultaneously. Dynamic moisture conditions can therefore alter wall heat transfer and building-energy demand [5]. Coupled heat and moisture transfer (HAMT) modeling has consequently become an important method for evaluating the transient hygrothermal performance of building envelopes [6]. Reviews show that HAMT models provide a more realistic representation of material states and their feedback on building loads, but predictions remain sensitive to material properties, boundary conditions, modeling assumptions and numerical implementation [7–9]. HAM benchmark studies further demonstrate that alternative physical descriptions and computational schemes can yield appreciably different results, making model validation and defensible boundary conditions essential [10]. Climate-driven changes in rainfall, atmospheric humidity and temperature extremes may also intensify moisture accumulation, material degradation and mold risk [11,12]. Dry-material properties and steady-state thermal transmittance alone therefore cannot describe the long-term behavior of exterior walls under real weather forcing.

1.1. Effects of Coupled HAMT on Building-Envelope Performance

HAMT models link external weather forcing to internal wall moisture by simultaneously resolving heat transfer, water-vapor diffusion, and liquid-water transport. Moisture accumulation can increase condensation and mold risk while changing effective thermal conductivity and heat-flow response, thereby limiting the applicability of heat-only models [13]. Wind-driven rain (WDR) is a major source of liquid water at exterior walls. Dynamic WDR boundaries can substantially affect surface absorption, internal moisture distributions, and heating and cooling loads [14]. Actual rainwater penetration also depends on exterior-finish materials, pressure differences and construction defects [15]. Building geometry, facade orientation, surrounding shelter and local wind fields create further spatial heterogeneity in WDR deposition [16,17]. Moreover, the temporal resolution of weather data, the treatment of wind speed and direction, and the choice of semi-empirical model all affect WDR estimates [18]. Comparisons among field measurements, computational fluid dynamics and semi-empirical models also reveal biases associated with rainfall type and data averaging [19]. When alternative WDR algorithms are coupled to HAM models, predicted wall moisture, heat loss and mold risk change accordingly [20]. Exterior boundaries should therefore represent weather variability, material moisture uptake and uncertainty in WDR modeling rather than rely on fixed rain inputs or oversimplified moisture fluxes.

1.2. Effects of Environmental Longwave Radiation on Hygrothermal Response

Alongside solar shortwave radiation and WDR, environmental longwave radiation (ELR) is an important component of the exterior-surface energy balance. Outdoor radiation fields are directional and spatially heterogeneous [21], while net longwave exchange between a wall and the sky is governed jointly by effective sky temperature, atmospheric water vapor and cloud cover [22]. Zhao et al. showed that explicit treatment of facade longwave exchange can substantially alter the surface energy balance [23]. Xie et al. further found that neglecting inter-building longwave exchange in dense cities can affect predictions of surface temperature, building-energy use and overheating risk [24]. All-sky longwave models reveal marked temporal variation among sky states [25]. Field studies also show that precipitation, orientation, surface aging and actual exposure conditions modulate radiative cooling at building surfaces [26,27]. Measurements of coastal facades further emphasize the importance of local water vapor and sky state in longwave-radiation modeling [28]. Recent HAMT research likewise indicates that commonly

simplified environmental factors, including sky longwave radiation, can produce non-negligible errors in envelope predictions [29].

On clear or lightly cloudy nights, a wall continuously emits longwave radiation to a sky with a lower effective temperature, allowing its exterior surface to cool below the outdoor air. This cooling increases the sensible-heat-transfer driving force, lowers local saturation vapor pressure and raises relative humidity (RH). It can thereby alter water-vapor diffusion, adsorption and desorption, capillary transport and phase change. ELR is therefore not merely an independent supplementary heat boundary. It can affect internal wall conditions through a coupled pathway of radiative cooling, surface humidification and internal moisture migration. Because atmospheric water vapor, cloud cover, solar radiation and diurnal temperature range differ substantially among climates, both the magnitude and direction of ELR effects may be strongly climate-dependent.

1.3. Moisture Accumulation and Mold Risk

Moisture safety cannot be assessed from instantaneous RH or a condensation threshold alone. Long-term damage also depends on the weather sequence, the duration of temperature and humidity exposure, and material sensitivity. The selected moisture reference year can alter long-term hygrothermal risk estimates [30]. The reliability of substituting a design reference year for long weather records likewise depends on the climatic period and assessment metric [31]. Under historical and future climates, mold risk is sensitive to both meteorological variables and model uncertainty [32]. Studies of real roofs further show that changes in insulation and ventilation can raise local RH and amplify mold risk [33]. Continuous monitoring systems provide complementary evidence for diagnosing long-term hygrothermal conditions, energy use and environmental performance [34]. Coupling hourly HAMT results to a mold model that accounts for cumulative temperature, humidity and exposure duration can therefore extend assessment from transient moisture variations to long-term durability risk.

1.4. Research Gaps and Objectives

Three gaps remain. First, under humid and near-saturated conditions, the effects of alternative moisture-driving potentials on liquid transport, interfacial moisture accumulation, and sensible and latent heat transfer have not been systematically compared. Second, ELR is still commonly represented by equivalent or simplified terms in HAMT analyses, and its feedback pathway from radiative cooling to local humidification and internal moisture migration lacks quantitative evidence across climates. Third, existing longwave-radiation studies focus mainly on surface temperature and building-energy use, with less attention to long-term mold risk and propagation into the wall. Few studies integrate WDR, ELR, hygrothermal loads and mold risk within a single assessment framework.

To address these gaps, a transient HAMT model for multilayer walls is developed using temperature and capillary pressure as the primary variables. Hourly sky longwave radiation, solar shortwave radiation and WDR are incorporated into a dynamic exterior boundary, and a mold-growth model is used to evaluate long-term risk at the exterior surface and key internal nodes. Comparative simulations for the contrasting climates of Harbin and Guangzhou quantify the effects of ELR on transient temperature and humidity, annual sensible and latent heat transfer, and mold risk. The main contributions are threefold: (1) clarifying the influence of moisture-driving potential under high-humidity conditions; (2) revealing the climate-dependent ELR pathway from radiative cooling to coupled heat and moisture redistribution; and (3) linking transient HAMT responses to long-term mold risk using the VTT model. The study proceeds through model develop-

ment and validation, ELR sensitivity analysis, hygrothermal-response assessment, and VTT-based mold-risk evaluation across the two climates.

2. Mathematical Formulation and Numerical Methodology

2.1. Coupled Heat and Moisture Transfer Model

The building wall is represented as a one-dimensional transient system composed of multiple unsaturated porous materials. The analysis focuses on the central region of a large wall, away from windows, corners, and structural thermal bridges. Each layer is assumed to be continuous, homogeneous and isotropic, with no appreciable deformation or chemical reaction of the solid skeleton. Pore water exists in vapor and liquid phases; the gas phase obeys the ideal-gas relation, whereas the liquid phase is treated as incompressible. All phases are assumed to be in local thermodynamic equilibrium, and temperature and hygrothermal fluxes are continuous across material interfaces. For an intact wall without major cracks or air-leakage paths, macroscopic airflow and gravity-driven liquid transport through the wall thickness are neglected. The formulation builds on the coupled heat and mass transfer frameworks of Philip and De Vries, Luikov, and Cary [35–37], together with Pedersen’s description of water-vapor diffusion and liquid-water transport [38].

Temperature (T) and capillary pressure (p_c) are selected as the primary variables to describe moisture continuously across the hygroscopic and near-saturated ranges and to improve numerical stability at interfaces between dissimilar materials. From the Kelvin thermodynamic relation:

$$\varphi = \exp \left(\frac{p_c}{\rho_l R_v T} \right) \quad (1)$$

$$p_v = \varphi p_{sat}(T) \quad (2)$$

where φ is relative humidity (dimensionless); p_c is capillary pressure (Pa); ρ_l is liquid-water density (kg/m^3); R_v is the specific gas constant for water vapor ($\text{J}/(\text{kg}\cdot\text{K})$); T is absolute temperature (K); p_v is water-vapor partial pressure (Pa); and p_{sat} is saturation vapor pressure at temperature T (Pa).

Moisture transport within the material comprises water-vapor diffusion and capillary liquid-water transport. Vapor diffusion is driven by the partial-pressure gradient, whereas liquid-water transport is governed mainly by the capillary-pressure gradient:

$$g_v = -\delta_v \nabla p_v \quad (3)$$

$$g_l = -K_l \nabla p_c \quad (4)$$

where g_v is water-vapor mass flux ($\text{kg}/(\text{m}^2\cdot\text{s})$); g_l is liquid-water mass flux ($\text{kg}/(\text{m}^2\cdot\text{s})$); δ_v is water-vapor permeability ($\text{kg}/(\text{m}\cdot\text{s}\cdot\text{Pa})$); and K_l is liquid-water conductivity

(kg/(m·s·Pa)).

Evaporation and condensation redistribute mass between the vapor and liquid phases but do not change the total water mass within the control volume. Moisture conservation is therefore expressed as:

$$\frac{\partial w}{\partial t} + \nabla \cdot (g_v + g_l) = 0 \quad (5)$$

where w is the total volumetric moisture content of the material (kg m⁻³) and t is time

(s). The moisture-storage relation is written as $w = w(T, p_c)$. During calculation, moisture capacity, water-vapor permeability and liquid-water conductivity are updated dynamically with moisture state to represent the transition from hygroscopic control to capillary transport [39].

According to the first law of thermodynamics, energy changes within the porous material result from conduction through the solid skeleton and enthalpy transported by vapor and liquid water. In total-enthalpy form, energy conservation is expressed as:

$$\frac{\partial H}{\partial t} + \nabla \cdot [-\lambda \nabla T + h_v g_v + h_l g_l] = 0 \quad (6)$$

where H is the total volumetric enthalpy of the porous material (J/m³); λ is the effective

thermal conductivity (W/(m·K)); and h_v and h_l are the specific enthalpies of water vapor and liquid water (J/kg), respectively. The conduction term represents sensible heat transfer, vapor transport includes enthalpy exchange associated with phase change, and liquid-water transport carries sensible heat. Thermal conductivity varies with moisture content, while temperature changes the moisture-driving potential through saturation vapor pressure and the Kelvin relation. These interactions produce two-way coupling between the thermal and moisture fields.

2.2. Dynamic Boundary Conditions Including Environmental Longwave Radiation

Longwave radiation incident on an exterior wall originates mainly from the sky vault and from surrounding ground and buildings. In dense urban settings, ground radiation may be restricted by building obstruction, and temperature differences among adjacent environmental surfaces are often comparatively small. The model therefore focuses on the dominant sky longwave component. The exterior wall surface exchanges heat and moisture through air convection, water-vapor transfer, solar shortwave radiation, sky longwave radiation and WDR. With moisture flux into the wall defined as positive, the exterior moisture flux is:

$$g_e = \beta_e (p_{v,e} - p_{v,s}) + R_{wdr} \quad (7)$$

where g_e is the total exterior-surface moisture flux (kg/(m²·s)); β_e is the exterior convective mass-transfer coefficient (kg/(m·s·Pa)); $p_{v,e}$ and $p_{v,s}$ are the water-vapor partial pressures of the outdoor air and exterior wall surface (Pa), respectively; and R_{wdr} is the

WDR mass flux intercepted by the wall ($\text{kg}/(\text{m}^2\cdot\text{s})$). WDR is calculated using the ISO semi-empirical method based on wind speed, wind direction, horizontal rainfall and facade orientation [40,41]. Effects of terrain roughness, surrounding obstruction, eaves and facade characteristics are represented by empirical correction factors. These factors are set to unity to isolate climatic and ELR effects; consequently, site-specific WDR redistribution caused by urban shielding and surface detailing is not explicitly resolved.

The exterior-surface energy balance includes air convection, solar shortwave gain, sky longwave loss, water-vapor transfer and sensible heat exchange with rainwater:

$$q_e = h_e (T_e - T_s) + \alpha_{\text{sol}} I_v - q_{\text{LW}} + h_v \beta_e (p_{v,e} - p_{v,s}) + c_{\text{pl}} R_{\text{wdr}} (T_{\text{wdr}} - T_s) \quad (8)$$

where q_e is the total exterior-surface heat flux (W/m^2); h_e is the exterior convective heat-transfer coefficient ($\text{W}/(\text{m}^2\cdot\text{K})$); T_e and T_s are the outdoor-air and exterior-surface temperatures (K), respectively; α_{sol} is the solar shortwave absorptivity of the exterior surface (dimensionless); I_v is the solar shortwave irradiance incident on the vertical wall (W/m^2); q_{LW} is the net longwave radiative heat flux between the wall surface and sky (W/m^2); c_{pl} is the specific heat capacity of liquid water ($\text{J}/(\text{kg}\cdot\text{K})$); and T_{wdr} is the WDR temperature (K).

Net sky longwave radiation is calculated from the Stefan-Boltzmann law:

$$q_{\text{LW}} = \varepsilon \sigma F_{\text{sky}} (T_s^4 - T_{\text{sky}}^4) \quad (9)$$

where ε is the longwave emissivity of the exterior surface (dimensionless); σ is the Stefan-Boltzmann constant, $5.670 \times 10^{-8} \text{ W}/(\text{m}^2\cdot\text{K}^4)$; F_{sky} is the wall-to-sky view factor; and T_{sky} is the effective sky radiative temperature (K).

For a surface inclined at angle θ :

$$F_{\text{sky}} = \frac{1 + \cos \theta}{2} \quad (10)$$

The wall considered here is vertical, so $\theta = 90^\circ$ and $F_{\text{sky}} = 0.5$. Because the real sky is not an ideal blackbody, its effective radiative state depends jointly on air temperature, atmospheric water vapor and cloud cover. T_{sky} is therefore determined dynamically from hourly air temperature, dew point and cloud cover [42,43]. To isolate sky radiative cooling, the model does not explicitly resolve a multi-surface radiation network involving neighboring buildings and the ground. The results therefore represent a typical facade

with substantial sky exposure.

The indoor environment is comparatively stable and receives neither solar radiation nor liquid-water input from WDR. Indoor moisture and heat exchange are therefore expressed as:

$$g_i = \beta_i (p_{v,i} - p_{v,si}) \quad (11)$$

$$q_i = h_i (T_i - T_{si}) + h_v \beta_i (p_{v,i} - p_{v,si}) \quad (12)$$

where h_i and β_i are the indoor convective heat- and mass-transfer coefficients, respectively.

2.3. Mold Growth Risk Assessment

To translate ELR-induced transient hygrothermal changes into a long-term moisture-safety metric, hourly temperature and RH at each monitored node are supplied to the extended VTT mold model. The classic model of Hukka and Viitanen combines the effects of temperature, RH and exposure duration on mold growth [44]. Vereecken and Roels further showed that critical humidity, cumulative exposure time and decay during drying all influence risk classification [45]. The extended VTT model classifies building materials as Very Sensitive, Sensitive, Medium Resistant or Resistant [46], allowing materials to respond differently to the same temperature and humidity history. The model has also been coupled with HAMT models for long-term moisture-risk assessment of building materials [47].

In the present study, all monitoring nodes P1–P5 were assigned to the Medium Resistant (MR) sensitivity class to maintain a consistent mold-sensitivity assumption across the wall. Accordingly, the minimum relative-humidity threshold was set to

$RH_{min} = 85\%$. For the non-wood building materials considered here, the surface-quality

parameter was set to $SQ = 0$, and the initial mold index was $M = 0$. Mold growth was ac-

tivated when $T > 0^\circ\text{C}$ and $RH > RH_{crit}$. When $T \leq 0^\circ\text{C}$ and $RH \leq RH_{crit}$, mold growth ceased and the decline formulation of the extended VTT model was applied. Hourly temperature and RH obtained from the HAMT simulations were sequentially supplied to the VTT model to update the mold index throughout the annual calculation.

Mold development is represented by a dimensionless index M ranging from 0 to 6. The index increases with exposure time when temperature and RH satisfy the material-specific growth conditions. Under unfavorable conditions, growth ceases and the index may decline. The annual maximum mold index is defined as:

$$M_{max} = \max [M(t)] \quad (13)$$

where $M(t)$ is the dimensionless mold-growth index at time t ; M_{max} is the maximum mold-growth index over the calculation period; and $\max$ denotes the maximum over the study period. M_{max} is used to compare annual risk. Unlike the instantaneous maximum

RH, this metric captures the cumulative effects of periodic radiative cooling, prolonged humidity, and intervening drying.

2.4. Numerical Implementation and Simulation Cases

The nonlinear governing equations for coupled heat and moisture transfer are solved using a fully coupled finite-element method. The nonlinear governing equations for coupled heat and moisture transfer were solved using a fully coupled finite-element method. The wall model was discretized into 10,400 finite elements. Mesh sensitivity was examined using 8000, 10,400, and 13,000 elements. Further refinement from 10,400 to 13,000 elements produced no appreciable change in the principal temperature and RH responses; therefore, 10,400 elements were adopted for the subsequent simulations. An implicit time-integration scheme with a maximum time step of 900 s was used, and convergence was achieved with a relative tolerance of 10^{-4} . The vector of primary variables

is: $\mathbf{u}=[T, p_c]^T$. Outdoor boundary inputs comprise hourly typical meteorological year data for air temperature, RH, solar radiation, wind speed, wind direction, and rainfall. Material thermal and moisture properties are updated dynamically according to the instantaneous state. To isolate the effect of ELR, Case N-LW denotes the case without explicit sky longwave radiation, whereas Case LW denotes the case with dynamic sky longwave radiation. The two cases use identical wall construction, material properties, indoor conditions, solar radiation and WDR. Outputs include exterior-surface temperature and humidity, the temperature difference across the wall, sensible and latent heat fluxes, and mold indices at key nodes. These outputs provide a consistent basis for comparison between Harbin and Guangzhou.

3. Model Setup and Validation

3.1. Model Setup and Boundary Conditions

To compare ELR effects on envelope hygrothermal response across climates, a typical externally insulated composite wall is constructed using the one-dimensional transient HAMT equations described in Section 2. The model represents the central region of a large wall, away from windows, corners, and local thermal bridges, and is discretized through the wall thickness using finite elements. The exterior-insulated configuration serves as a representative multilayer wall; thermal-bridge mitigation at junctions is not evaluated because such multidimensional effects fall outside the scope of the one-dimensional model. From outside to inside, the wall comprises 20 mm of cement mortar, 20 mm of expanded polystyrene (EPS) insulation, a 200 mm structural substrate and 20 mm of cement mortar. The structural substrate is aerated concrete in Harbin, ordinary concrete in Guangzhou and clay brick in the supplementary Wuhan case to represent regionally typical wall configurations, while the common cement-mortar and EPS layers are retained across cases. Because the substrates differ, cross-city differences may reflect both climatic and material effects. Accordingly, the ELR effect is primarily evaluated through the within-city comparison between Case LW and Case N-LW, where all other model inputs are identical.

Five monitoring nodes, P1-P5, are distributed through the wall thickness (Figure 1). P1 is located at the exterior surface and is directly exposed to outdoor temperature and humidity, solar radiation, ELR, and WDR. P2 is located at the exterior mortar/EPS interface and characterizes the response after exterior moisture perturbations enter the insulation system. P3 and P4 are located at the EPS/structural-substrate and structural-substrate/interior-mortar interfaces, respectively, whereas P5 is located at the interior surface. Hourly temperature, RH and capillary pressure are extracted at each node for

subsequent analyses of hygrothermal transport and mold risk. The exterior boundary includes convective heat transfer, water-vapor exchange, solar shortwave radiation, sky longwave radiation and WDR. The interior boundary includes air convection and water-vapor exchange, thereby directly coupling external weather forcing to heat and moisture migration within the wall.

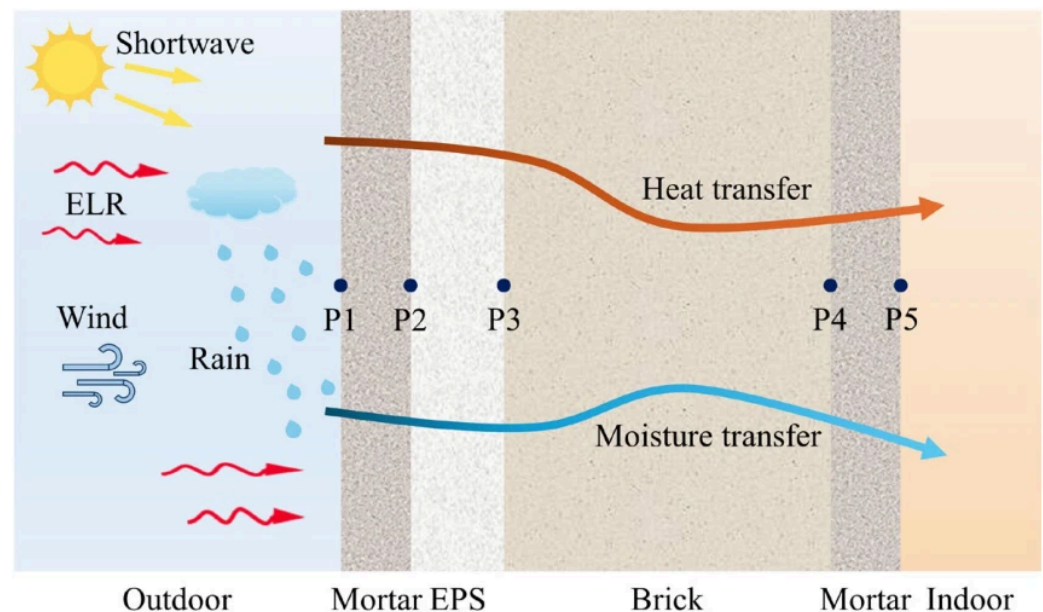


Figure 1. Physical model of the building envelope, boundary conditions and monitoring locations.

Tables 1 and 2 summarize the basic thermal and moisture properties of the materials. Cement mortar and EPS are common functional layers in all climate cases, whereas the structural substrate varies by city. Density, specific heat capacity and thermal conductivity are given in Table 1. Water-vapor diffusion resistance, vapor permeability, liquid-water conductivity and related moisture properties are listed in Table 2. During the simulations, thermal and moisture transport properties are updated according to instantaneous moisture state to represent the nonlinear hygrothermal behavior of porous materials.

Table 1. Basic thermophysical properties of the wall materials used in the simulations.

Structural Configuration	City	Material	Basic Physical Properties		
			ρ	c_p	λ
Differentiated base layer materials	Guangzhou	Concrete	2130	730	$0.55 + 0.0008\mu$
	Harbin	Aerated concrete	650	776	$0.118 + 0.001\mu + 0.000$
Common functional layer materials	General	Cement mortar	1880	850	$0.6 + 0.0032\mu + 0.0002$
		EPS	20	1500	$0.0377 + 0.0022\mu$

Table 2. Moisture-transport properties of the wall materials used in the simulations.

Structural Configuration	City	Material	Moisture Properties		
			μ	δ	K_l
Differentiated base layer materials	Guangzhou	Concrete	$\ln \frac{(100\varphi + 1)^{4.78}}{(1 - \varphi)^{19.69}}$	$3.4e^{-12} + 1.1e^{-11}\varphi^{6.34}$	$1.7e^{-12} \times \left(\frac{\mu}{201}\right)^{9.89}$
	Harbin	Aerated concrete	$\ln \frac{(100\varphi + 1)^{0.515}}{(1 - \varphi)^{3.15}}$	$3.99e^{-11} + 1.72e^{-11}\varphi^{3.89}$	$1.3e^{-7} \times \left(\frac{\mu}{745}\right)^{14.43}$
Common functional layer materials	General	Cement mortar	$\ln \frac{(100\varphi + 1)^{1.76}}{(1 - \varphi)^{12.32}}$	$5.57e^{-12} + 2.14e^{-10}\varphi^{25.89}$	$1.27e^{-9} \times \left(\frac{\mu}{280}\right)^{13.6}$
		EPS	$\ln \frac{(100\varphi + 1)^{0.034}}{(1 - \varphi)^{0.021}} + 5.66e^{-41} * \exp(100\varphi)$	$4.92e^{-12} + 7.05e^{-12}\varphi^{6.11}$	–

The exterior boundary is prescribed using hourly typical meteorological year data for air temperature, RH, solar radiation, wind speed, wind direction and rainfall. During the heating season, indoor temperature is set to 18 °C from 06:00 to 20:00 and 17 °C from 20:00 to 06:00, with RH maintained at 50%. During the cooling season, daytime and nighttime temperatures are 26 °C and 27 °C, respectively, with RH maintained at 60%. Initial wall temperature and moisture state are equilibrated with the indoor environment. Case N-LW and Case LW are used to isolate the effect of ELR. Wall construction, material properties and all other boundary conditions are identical between cases.

3.2. HAMSTAD Benchmark Validation

HAMSTAD benchmark case 5 is used to validate moisture transport across interfaces between dissimilar materials and moisture accumulation under high-humidity conditions [48]. The benchmark wall comprises 365 mm of brick masonry, 15 mm of mortar and 40 mm of insulation. Large differences in the moisture-storage and transport properties of these materials provide a stringent test of nonlinear interface treatment. The wall is initially in hygrothermal equilibrium. Outdoor conditions are 0 °C and 80%

RH, whereas indoor conditions are 20 °C and 60% RH. Exterior and interior convective heat-transfer coefficients are 25 and 8 W/(m²·K), respectively, with corresponding mass-transfer coefficients of 1.84×10^{-7} and 5.88×10^{-8} s/m. All nonlinear material properties follow the benchmark specification.

Figure 2 compares the HAMSTAD reference results after 60 days with predictions from the RH-driven and capillary-pressure-driven models. Both models reproduce the reference RH and moisture-content profiles in the normal hygroscopic range below approximately 95% RH, but their predictions diverge under highly humid or near-saturated conditions. As RH approaches unity, its gradient becomes less sensitive to changes in liquid-water content even though material moisture content can continue to increase. By contrast, capillary pressure retains a continuous moisture-potential gradient near saturation and more accurately represents liquid-water transport and accumulation at material interfaces. A formulation driven by p_c is therefore better suited to the subsequent analysis of highly humid walls exposed to WDR.

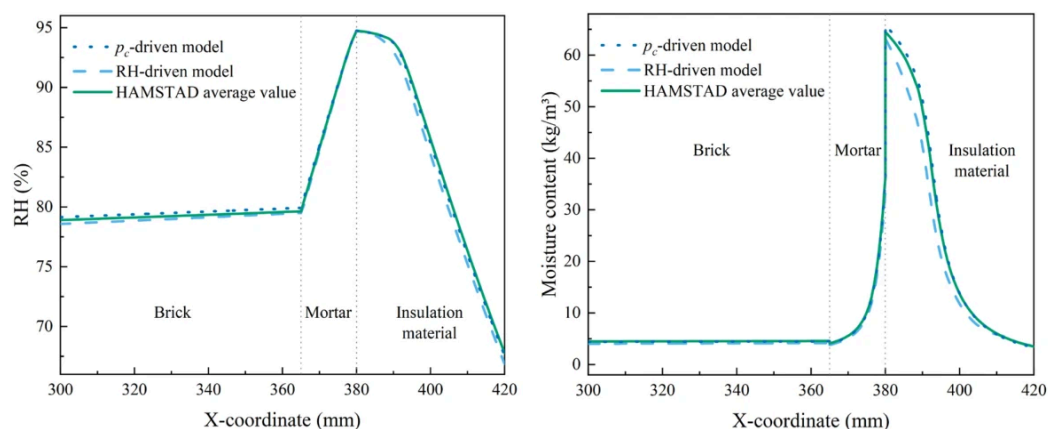


Figure 2. HAMSTAD benchmark case 5 and comparison of RH and moisture-content distributions after 60 days.

3.3. Validation Against Field Measurements

The model is further validated against long-term field measurements from an exterior wall at the Technical University of Denmark [49,50]. The southwest-facing Wall 2 is exposed to WDR and intermittent solar radiation. From outside to inside, the assembly comprises 108 mm of brick masonry, 4 mm of lime mortar, 228 mm of brick masonry, 10 mm of lime mortar, 8 mm of lightweight mortar, a 100 mm insulation board and 8 mm of lightweight mortar. Monitoring points P1–P4 are located 54, 177, 353 and 464 mm from the exterior surface, respectively. HYT221 sensors measure RH and temperature with accuracies of $\pm 1.8\%$ RH and ± 0.2 °C. Figure 3 shows the construction and sensor locations. Long-term WDR exposure drives RH close to 99.9% at P1–P3 during some periods, whereas P4 remains mainly within 60–80% RH. The wall therefore spans both the normal hygroscopic and near-saturated ranges and provides a demanding test of model applicability.

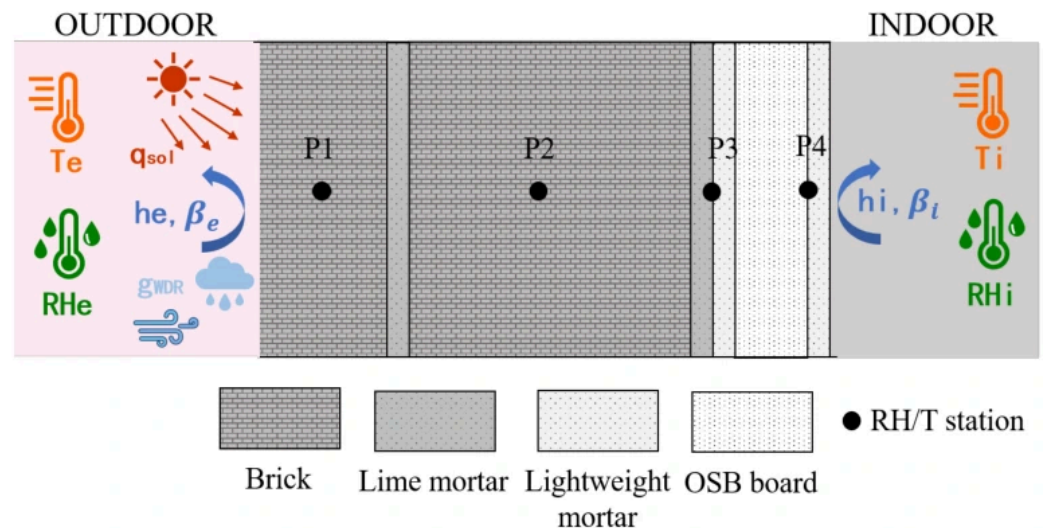


Figure 3. Physical configuration of the experimental wall and monitoring-point locations.

Measured hourly outdoor air temperature, RH and WDR during the experiment are imposed as exterior boundary conditions. Indoor RH decreases in stages from approximately 70% to 60% according to the experimental control protocol. The boundary time series are shown in Figure 4. Moisture-storage curves, water-vapor permeability and liquid-water conductivity for the wall materials are shown in Figure 5, and their nonlinear variation is incorporated directly into the transient calculations.

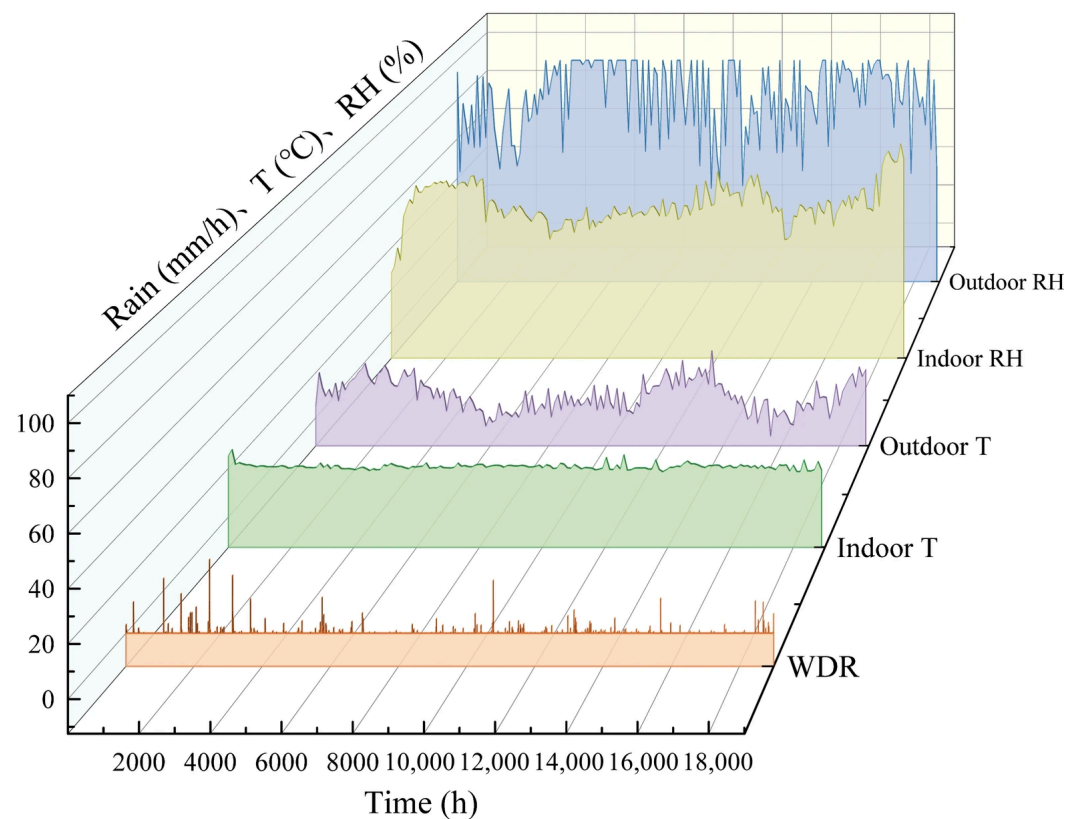


Figure 4. Measured indoor and outdoor boundary conditions used for field validation.

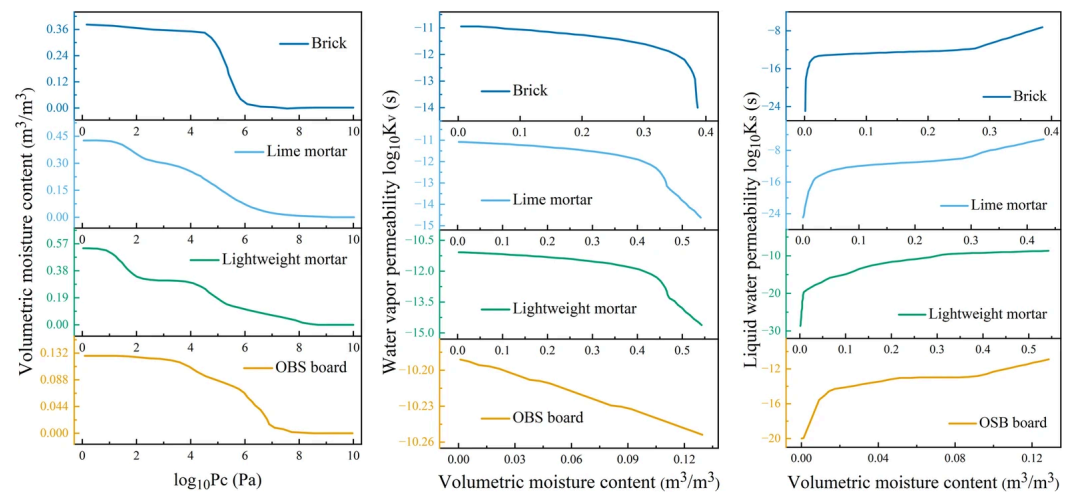


Figure 5. Hygrothermal properties of the experimental-wall materials.

Figure 6 shows that the model reproduces the main temperature and RH variations at P1–P4, including rainfall-induced humidification, subsequent drying, and attenuation of exterior temperature fluctuations through the wall. Table 3 summarizes the statistical errors. Temperature NMBE ranges from -5.02% to 1.08% , with CVRMSE ranging from 3.04% to 10.35% . For RH, NMBE ranges from -0.91% to 2.14% , while CVRMSE ranges from 1.33% to 7.34% . Exterior node P1 exhibits the largest temperature CVRMSE (10.35%) and RH RMSE (7.05 percentage points), consistent with its direct exposure to rapidly varying solar radiation and WDR. Temperature errors generally decrease toward the interior, reaching an RMSE of $0.56\text{ }^{\circ}\text{C}$ at P4, whereas RH errors vary with material interfaces and moisture transport. Short-term discrepancies during rainfall and subsequent drying are partly attributable to the spatially averaged boundary conditions adopted in the one-dimensional model. Together with the HAMSTAD comparison, these results support the coupled HAMT model under dynamic meteorological forcing. However, the available field measurements did not permit a separate assessment of the sky longwave-radiation formulation.

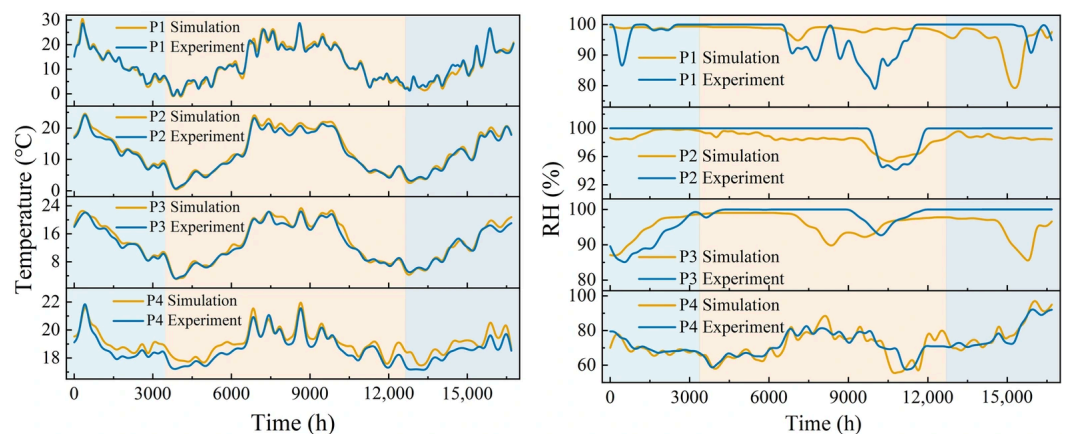


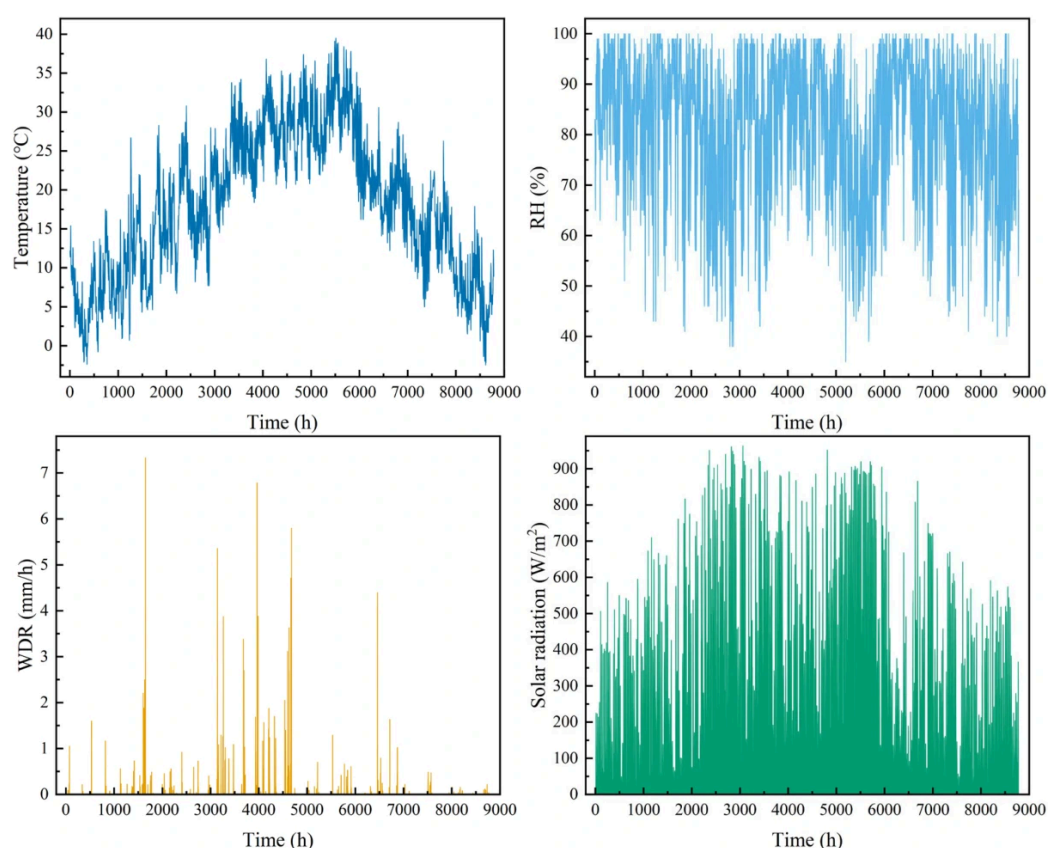
Figure 6. Comparison of simulated and measured temperature and RH at the monitoring locations.

Table 3. Statistical evaluation of simulated temperature and relative humidity against field measurements.

Point	Temperature RMSE (°C)	Temperature NMBE (%)	Temperature CVMSE (%)	RH RMSE (%)	RH NMBE (%)	RH CVMSE (%)
P1	1.25	1.08	10.35	7.05	−0.91	7.34
P2	1.05	−5.02	8.67	1.31	0.97	1.33
P3	1.17	−4.24	9.02	4.72	2.14	4.86
P4	0.56	−2.40	3.04	4.93	0.35	6.82

3.4. Comparison of RH-Driven and Capillary-Pressure-Driven Models

Material moisture state and moisture transport can affect predicted heating and cooling loads through walls [51]. Accordingly, a supplementary numerical experiment is conducted under the typical climate of Wuhan to assess how the selected moisture-driving potential influences annual hygrothermal results. The RH-driven and p_c -driven models use identical wall construction, material properties and exterior boundaries. Indoor conditions are 25 °C and 60% RH in summer and 18 °C and 50% RH in winter. Figure 7 shows the principal meteorological inputs for the Wuhan typical meteorological year. Their seasonal variation in temperature, humidity, solar radiation and rainfall provides the dynamic boundary for comparing the two formulations.

**Figure 7.** Principal outdoor meteorological parameters of the typical meteorological year in Wuhan.

Tables 4 and 5 compare the summer cooling loads and winter heating loads of the two formulations. Relative to the RH-driven model, the capillary-pressure-driven model reduces summer peak, mean and cumulative cooling loads by 4.39%, 4.67% and 4.75%, respectively, while increasing cumulative latent load by 6.14%. Winter peak, mean and cumulative heating loads rise by 4.05%, 9.01% and 9.03%, and latent load rises by 12.77%. The different predictions arise from liquid-water migration and retention, moisture-dependent thermal conductivity, and phase change, particularly under rain exposure or near saturation. Capillary pressure is therefore used in the subsequent Harbin and Guangzhou analyses.

Table 4. Comparison of summer cooling and latent loads predicted by the RH-driven and p_c -driven models in Wuhan.

Model	Peak Cooling Load (W/m ²)	Peak Change (%)	Cumulative Cooling Load (kWh/m ²)	Cumulative Change (%)	Average Cooling Load (W/m ²)	Average Change (%)	Cumulative Latent Load (kWh/m ²)	Latent Change (%)
RH-driven model	14.12	-	15.62	-	7.06	-	2.16	-
p_c -driven model	13.50	-4.39	14.88	-4.75	6.73	-4.67	2.29	6.14

Table 5. Comparison of winter heating and latent loads predicted by the RH-driven and p_c -driven models in Wuhan.

Model	Peak Heating Load (W/m ²)	Peak Change (%)	Cumulative Heating Load (kWh/m ²)	Cumulative Change (%)	Average Heating Load (W/m ²)	Average Change (%)	Cumulative Latent Load (kWh/m ²)	Latent Change (%)
RH-driven model	16.04	-	21.35	-	9.88	-	1.72	-
p_c -driven model	16.69	4.05	23.28	9.03	10.77	9.01	1.94	12.77

4. Results and Discussion

Case N-LW omits explicit sky longwave radiation, whereas Case LW includes hourly dynamic sky radiation; all other model inputs are identical. Harbin and Guangzhou represent severe-cold and hot-summer/warm-winter climates. Transient responses are examined during the three coldest days in Harbin (26–28 December) and three hottest days in Guangzhou (16–18 August). Annual sensible and latent transfer and VTT mold indices capture cumulative effects.

4.1. Effects of ELR on Building Hygrothermal Performance

4.1.1. Thermal Responses Across Climates

Exterior-surface temperatures during Harbin's three coldest days are shown in Figure 8a. Solar shortwave radiation rapidly warms the wall during the day, whereas sky

longwave radiation continuously removes heat from the surface. Exterior-surface temperature is therefore lower in Case LW than in Case N-LW during most periods. Once solar radiation disappears at night, longwave loss persists and the temperature difference between cases widens. At 06:00 on 26 December, the minimum exterior-surface temperature in Case LW reaches -28.33°C , approximately 1.28°C below Case N-LW, indicating pronounced radiative overcooling under cold, clear-sky conditions. Case LW also shifts the daytime temperature peak from 12:00 to 13:00. ELR therefore changes both surface temperature and the phase of the wall's dynamic response to solar input. Shortwave absorption, air convection and longwave loss jointly determine the exterior-surface energy balance. Longwave radiation primarily suppresses net daytime warming and provides sustained additional cooling at night, producing an asymmetric diurnal effect.

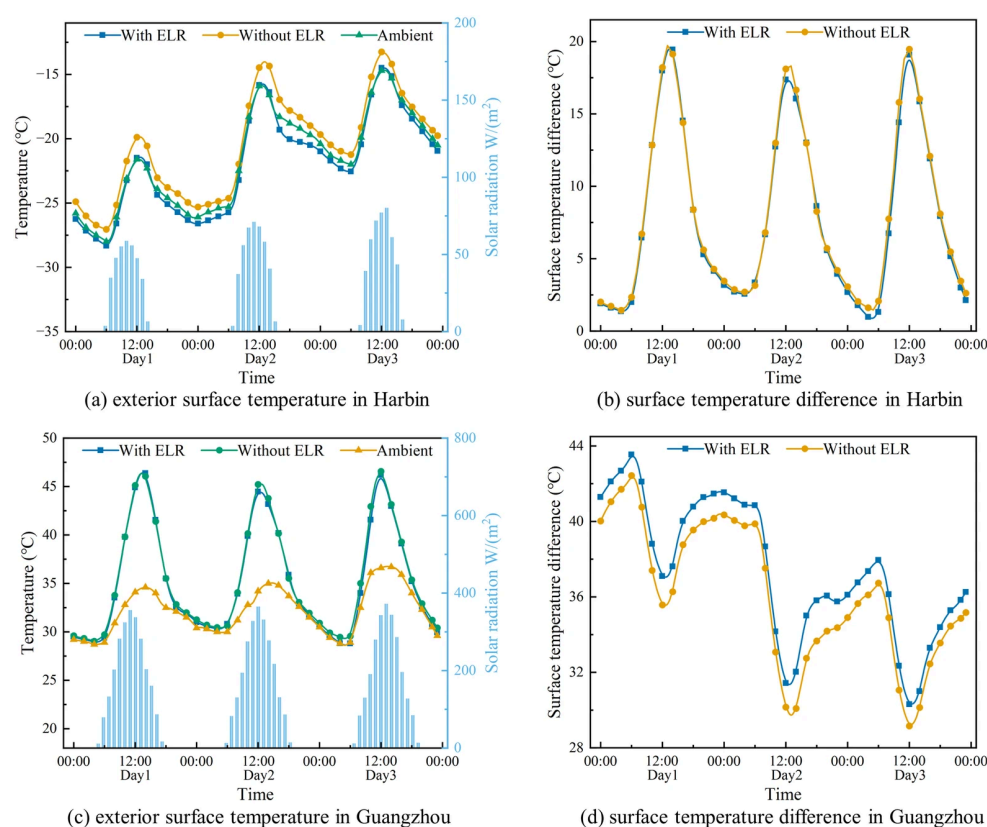


Figure 8. Dynamic thermal responses for Case LW and Case N-LW under different climatic conditions.

The largest difference in exterior-surface temperature does not coincide with the minimum outdoor-air temperature; instead, it occurs during the transition following the rapid decline in solar shortwave radiation. At 16:00 on 27 December, the temperature difference between cases is approximately 2.35°C . Solar input has weakened sharply, but the wall continues to emit longwave radiation toward a colder effective sky, causing Case LW to cool faster than Case N-LW. Without explicit ELR, the surface loses heat mainly through air convection and therefore cools more slowly. The largest thermal-boundary errors associated with neglecting ELR are therefore most likely around sunset and on clear nights rather than simply at the lowest air temperature. Daily mean temperature or a fixed combined heat-transfer coefficient can smooth these brief radiative-cooling events and underestimate surface perturbations. The minimum wall-surface temperature is jointly governed by outdoor-air temperature, effective sky temperature, short-wave radiation, and the wall's thermal inertia. Hourly ELR-induced temperature differ-

ences are consequently more relevant than daily means when assessing surface condensation, pre-freezing moisture conditions, and finish durability.

Figure 8b shows the temperature difference between the interior and exterior wall surfaces in Harbin. Indoor temperature remains comparatively stable during the heating season, whereas ELR cools the exterior surface and directly steepens the through-wall temperature gradient. Over the three coldest days, ELR increases this surface-to-surface temperature difference by as much as 2.25 °C, with a mean increase of 1.26 °C. Radiative cooling therefore strengthens the heat-transfer driving force throughout the cold period rather than only at isolated extremes. This effect promotes sensible heat transfer from indoors to outdoors and exposes near-exterior materials to more frequent low-temperature cycles. Thermal resistance and heat capacity in the exterior insulation and structural layers attenuate the perturbation toward the interior. The strongest ELR response is consequently concentrated at the exterior surface and nearby layers, providing a physical basis for the spatial attenuation of RH and mold risk discussed below.

The corresponding Guangzhou results are shown in Figure 8c,d. The temperature curves for the two cases nearly overlap, with a three-day mean exterior-surface difference of approximately 0.31 °C. At 13:00 on 16 August, when solar radiation is strongest, the surface-temperature difference is below 0.1 °C. Strong shortwave gain dominates the daytime surface energy balance, reducing the relative contribution of sky longwave loss. ELR nevertheless produces a detectable thermal response when shortwave radiation is weaker or the radiative temperature difference between the wall and sky is larger. At 10:00 on 18 August, the maximum ELR-induced change in the through-wall temperature difference is approximately 1.39 °C. High atmospheric humidity and greater cloud cover in Guangzhou raise the effective sky temperature and reduce net longwave exchange. Consequently, the thermal response to ELR is more pronounced in Harbin than in Guangzhou. ELR strength depends on both the effective wall-to-sky radiative temperature difference and the competition between longwave loss and solar shortwave gain. This contrast helps explain the different directions of annual sensible and latent responses in the two cities.

4.1.2. Moisture Responses Across Climates

ELR affects the moisture field primarily through changes in surface temperature. At a given water-vapor partial pressure, cooling lowers local saturation vapor pressure and raises RH. When the surface and near-surface layers remain humid, water-vapor diffusion, adsorption and desorption, and capillary liquid transport also adjust. Figure 9a shows that exterior-surface RH in Case LW is substantially higher than in Case N-LW during most of Harbin's three coldest days. With ELR, mean exterior-surface RH reaches 82.7%, approximately 9.1 percentage points above Case N-LW, and the peak rises from 91.4% to 99.7%, approaching saturation. Although ELR supplies no water directly, it can substantially alter surface moisture conditions by modifying the thermal boundary. Near saturation, even a small increase in RH can correspond to a marked increase in moisture content and stronger capillary transport. The 99.7% peak indicates conditions under which capillary liquid transport becomes increasingly important near the exterior. When WDR occurs simultaneously, rainwater input can coincide with ELR-induced cooling and reduced drying, thereby prolonging post-rain moisture retention.

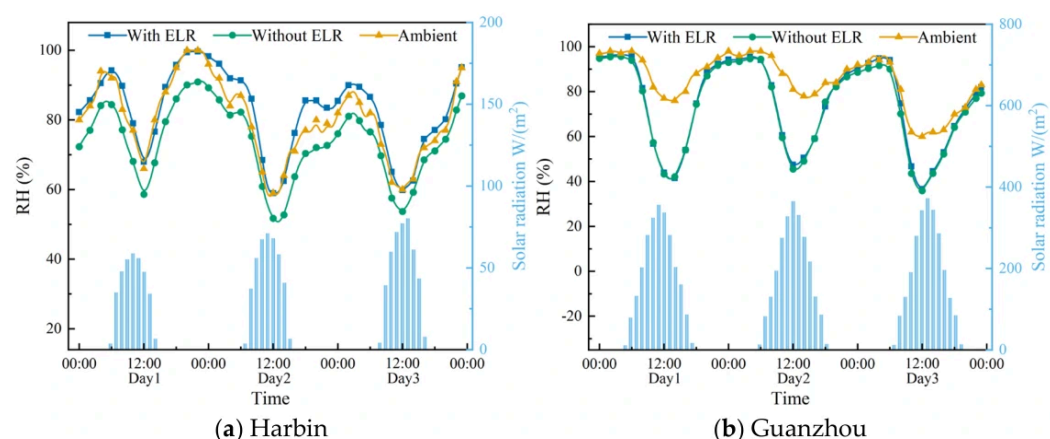


Figure 9. Dynamic exterior-surface RH at P1 for Case LW and Case N-LW under different climates.

The temperature and RH extremes at the Harbin exterior surface are not synchronous. The largest temperature difference between cases occurs at approximately 16:00, whereas the largest RH difference, approximately 15.2 percentage points, occurs at 18:00, indicating a lag of about 2 h. This lag reflects different response times in the thermal and moisture fields. Surface temperature responds rapidly to the radiative balance, but pore moisture must redistribute through adsorption, desorption, vapor diffusion and capillary transport. Radiative overcooling can therefore precede higher RH and prolonged humid exposure after sunset. When this sequence recurs, residual moisture from one episode can overlap with the next cooling event, creating a moisture-memory effect. Minimum temperature, maximum RH, and maximum moisture content need not coincide; consequently, a single-time criterion can miss cumulative humid periods. For mold risk, the duration of high humidity and its overlap with a favorable temperature range are more important than whether RH peaks during a particular hour.

The moisture response in Guangzhou is shown in Figure 9b. Exterior-surface RH curves for Case N-LW and Case LW are very similar. The peak rises only from 95.6% to 96.3%, and the maximum difference remains below one percentage point. Consistent with the thermal response, high atmospheric humidity and cloud cover raise effective sky temperature and weaken net longwave loss. ELR consequently produces only small changes in surface temperature and saturation vapor pressure. A weak instantaneous RH increment does not, however, imply that annual moisture effects are negligible. Guangzhou's high background humidity sustains strong moisture-transport conditions, and small but recurrent temperature changes can continually perturb vapor equilibrium and material moisture state. The sub-percentage-point RH difference during representative hot days must therefore be interpreted alongside annual latent heat transfer and mold index rather than judged solely by its instantaneous magnitude.

Harbin is thus characterized by strong radiative cooling, pronounced humidification and a delayed moisture response, whereas Guangzhou combines a weak transient increment with high background humidity. Individual perturbations are stronger in Harbin, but low temperature constrains some biological processes. In Guangzhou, smaller transient changes occur closer to adverse moisture thresholds because of the higher background humidity. Transient amplitude and long-term durability risk are therefore not linearly related. Climate also alters the relative importance of ELR and WDR. In severe-cold conditions, radiative cooling exerts stronger control over the surface-temperature gradient and RH. In hot-humid conditions, WDR and high ambient humidity maintain a higher moisture baseline, while ELR acts mainly through periodic radiative cooling and moisture redistribution. The two boundaries are complementary

rather than interchangeable, and their relative contributions vary with climate.

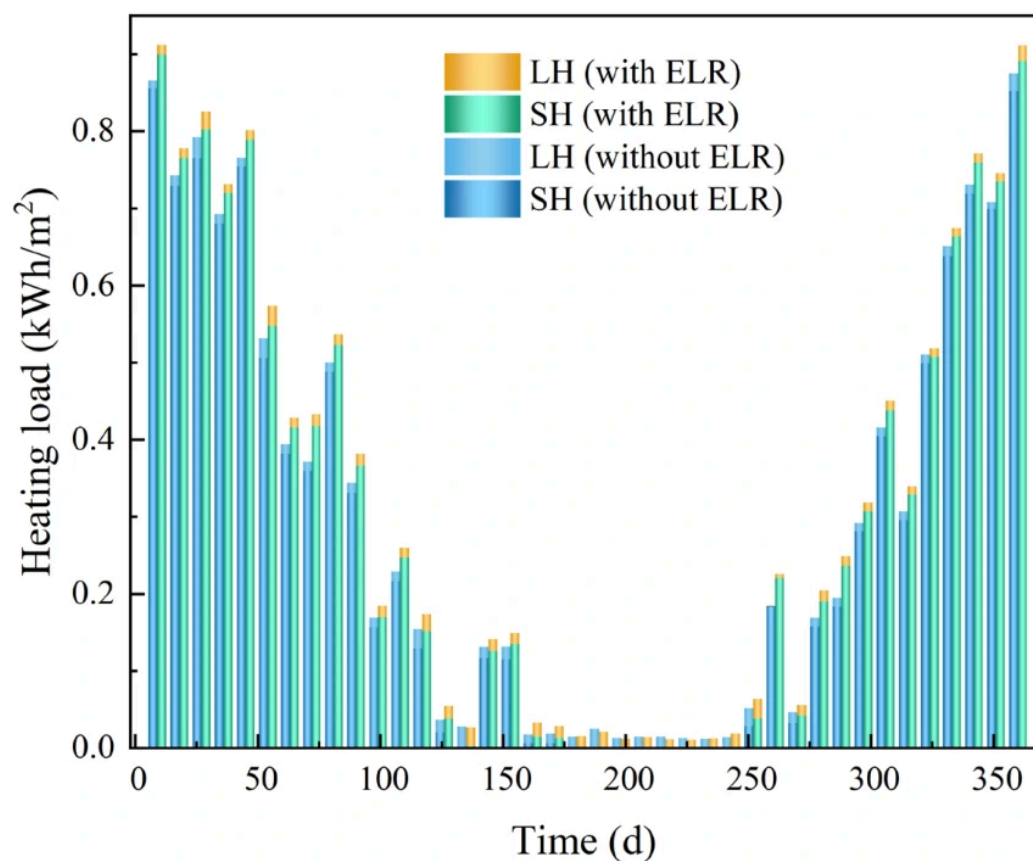
4.1.3. Hygrothermal Loads Across Climates

Transient temperature and humidity reveal the direct ELR pathway, whereas cumulative heat transfer reflects the integrated effect of repeated perturbations. The reported values represent directional seasonal totals obtained by integrating the hourly sensible and latent heat transfer at the interior wall surface over the heating season in Harbin and the cooling season in Guangzhou, respectively. Figure 10 compares the cumulative sensible and latent heat transfer between Case N-LW and Case LW. Harbin is dominated by heating demand and sensible heat transfer. Including ELR increases annual sensible heat transfer from 49.30 to 53.19 kWh/m², a rise of 7.88%, and latent heat transfer from 1.72 to 1.78 kWh/m², a rise of 3.33%. These results are consistent with the transient response during the three coldest days. Sky radiative cooling lowers the exterior-surface temperature, increases the through-wall temperature difference, and enhances conductive heat loss, whereas higher RH and more frequent near-saturation conditions promote moisture transport and enthalpy exchange associated with phase change. In absolute terms, ELR adds 3.89 kWh/m² of sensible heat transfer but only 0.06 kWh/m² of latent transfer. The annual energy difference is therefore dominated by sensible heat, although the increase in latent transfer confirms that the hourly moisture response accumulates over the year.

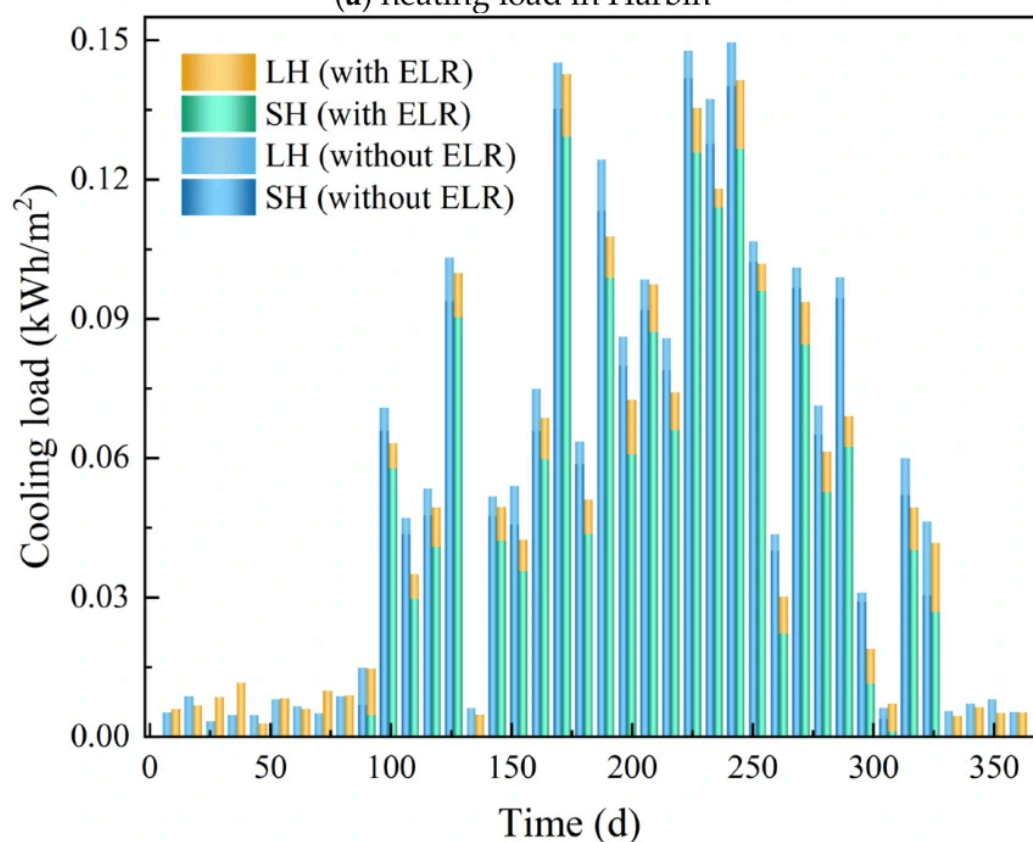
In Harbin, the 3.89 kWh/m² increase in annual sensible transfer greatly exceeds the 0.06 kWh/m² increase in latent transfer, indicating that the dominant energy effect of ELR is additional heat loss associated with a steeper temperature gradient. Moisture-dependent material properties and near-surface moisture transport also contribute to the coupled response, although they do not dominate the annual energy balance. Sensible and latent transfer nevertheless remain coupled because moisture alters material thermal properties while temperature governs moisture transport.

Guangzhou exhibits a different annual response. Including ELR decreases annual sensible heat transfer from 18.28 to 16.09 kWh/m², a reduction of 11.99%, while increasing latent heat transfer from 2.65 to 2.85 kWh/m², a rise of 7.54%. Although ELR has only a weak instantaneous thermal effect during representative hot days, net longwave loss still cools the exterior surface recurrently on clear nights, during transition seasons and under weak solar input. Individual perturbations may be 1–2 °C or smaller, but their repetition changes the annual sensible total. Periodic cooling in the humid environment also perturbs vapor equilibrium and promotes internal moisture redistribution, increasing latent transfer. The resulting decrease in sensible transfer and increase in latent transfer show that ELR primarily changes energy partitioning in a hot-humid climate. The absolute changes, −2.19 kWh/m² in sensible transfer and 0.20 kWh/m² in latent transfer, reflect compensation of net heat gain by longwave loss and more frequent moisture migration and phase change, respectively. An assessment based only on sensible demand could therefore misclassify this response as an unqualified thermal improvement while overlooking moisture transport, latent heat effects and material moisture safety.

The annual results reveal distinctly climate-dependent responses: ELR increases both sensible heat loss and latent transfer in Harbin, whereas it reduces sensible transfer but increases latent transfer in Guangzhou. The cold and hot spells identify transient mechanisms; annual integration establishes their cumulative energy effects (Figures 8–10). A small representative short-term temperature difference can therefore coexist with a measurable annual response.



(a) heating load in Harbin



(b) cooling load in Guangzhou

Figure 10. Sensible and latent heat transfer for Case LW and Case N-LW in Harbin and Guangzhou.

4.2. Mold Growth Risk Under Longwave Radiation

4.2.1. Exterior-Surface Mold Risk

Instantaneous RH identifies humid surface conditions but does not directly represent long-term biological durability because mold growth depends jointly on temperature, RH and exposure duration. The same RH peak can therefore have very different consequences in different seasons. Figure 11a shows the annual mold-index trajectory at exterior node P1 in Harbin. Although exterior-surface RH in Case LW rises substantially during winter and sometimes approaches saturation, very low temperatures strongly constrain mold activity, keeping the index low during the cold period. As temperature enters a favorable range in spring and early summer, retained moisture increasingly overlaps with suitable growth conditions and the mold index rises rapidly. Long-term risk is therefore governed by the temporal coincidence of temperature and humidity rather than by a single winter RH extreme. Hygrothermal differences established during the cold season become fully expressed as differences in mold index only after temperatures rise. This behavior reflects the VTT model's joint treatment of temperature, humidity and exposure duration and supports annual dynamic assessment rather than reliance on a single RH threshold.

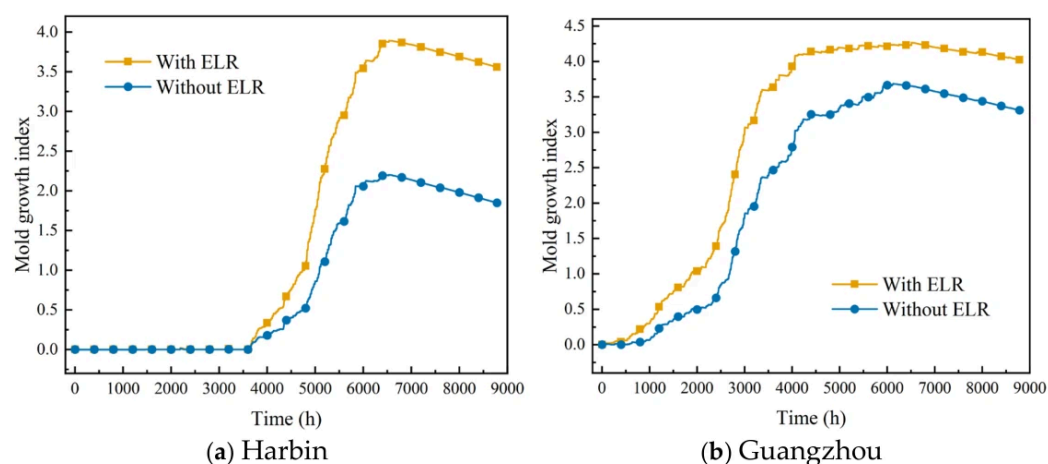


Figure 11. Annual mold-index evolution at exterior-surface node P1 for Case LW and Case N-LW in Harbin and Guangzhou.

At P1 in Harbin, the maximum mold index rises from 2.20 in Case N-LW to 3.89 in Case LW, an increase of 1.69 (76.8%). According to the VTT scale, this represents a transition from mainly microscopic mold growth to clearly visible mold growth. This exceeds the relative annual latent-transfer change because the mold model responds to the duration and seasonal coincidence of humidity and suitable temperature. Winter humidification can therefore contribute to risk that becomes apparent only in warmer periods. At P1 in Guangzhou, the maximum mold index increases from 3.69 to 4.27 (Figure 11b), an absolute rise of 0.58 or 15.7%. Both values correspond to visible mold growth, with the increase indicating more pronounced mold development. Its baseline and final indices exceed Harbin's, whereas its ELR-induced increment is smaller. Climate comparisons should distinguish baseline risk, absolute risk with ELR and sensitivity to the radiative boundary.

4.2.2. Mold Risk at Internal Interfaces

To determine whether ELR-induced hygrothermal perturbations propagate from the exterior surface into the wall, the annual maximum mold indices at P1-P5 are com-

pared (Figure 12). In Harbin, Case LW yields maximum values of 3.89, 0.23 and 0.12 at P1, P2 and P3, respectively, compared with 2.20, 0.11 and 0.07 in Case N-LW. P4 and P5 remain at zero in both cases. Mold risk therefore attenuates rapidly from the exterior inward, indicating that the thermal resistance, vapor resistance and moisture-storage capacity of the insulation and structural layers jointly buffer external hygrothermal forcing. Although absolute indices at P2 and P3 are low, both increase when ELR is included. Sky longwave radiation consequently affects not only the exposed surface but also near-exterior interfaces through coupled thermal and moisture transport.

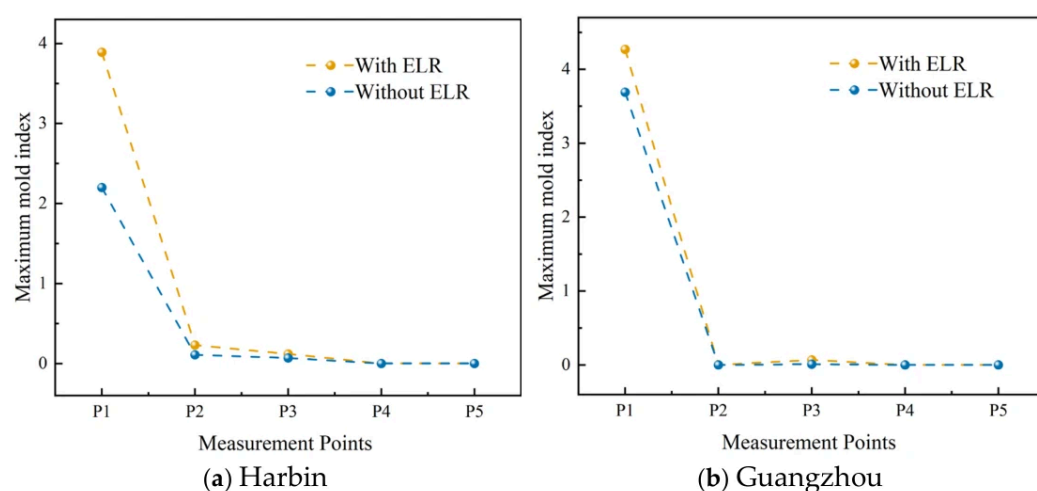


Figure 12. Maximum mold-growth index at wall nodes with and without sky longwave radiation.

Guangzhou is likewise dominated by P1, but the interface response does not decrease monotonically with depth. In Case LW, maximum mold indices at P1, P2 and P3 are 4.27, 0.002 and 0.068, respectively, compared with 3.69, 0 and 0.010 in Case N-LW. P4 and P5 remain at zero. The higher value at P3 than P2 shows that local interface risk depends not only on distance from the exterior but also on the vapor resistance, moisture storage, liquid-water conductivity, and temperature of adjacent materials. The high thermal resistance and characteristic vapor transport of EPS can promote local moisture redistribution where the insulation meets the structural substrate. Internal-node responses therefore need not decay linearly with depth. Although the P2 and P3 indices remain low, this non-monotonic response shows that interfaces should not be overlooked in multilayer hygrothermal analyses.

Maximum mold indices at P4 and P5 are zero in both cities. Under the intact one-dimensional wall and standardized boundary conditions considered here, ELR-induced hygrothermal perturbations remain insufficient to trigger mold growth at P4 and P5. This result does not imply that all internal nodes in real buildings are risk free. Windows, anchors, corners, cracks, air leakage and local thermal bridges can alter temperature and moisture pathways, but are not represented in the model. Figure 12 should therefore be interpreted as showing the relative attenuation of ELR effects through an intact wall rather than proving absolute safety at complex junctions. P2 and P3 remain important targets for design checks and long-term monitoring in humid, rain-exposed or construction-sensitive buildings. Their increases after ELR is included show that the radiative perturbation penetrates the assembly, where persistent low-amplitude moisture fluctuations may interact with material aging or local defects.

4.3. Climate-Dependent Mechanisms and Physical Implications

Together, Figures 8–12 define a continuous, cross-timescale ELR pathway. The wall first emits longwave radiation toward a sky with a lower effective temperature, changing the transient energy balance and exterior-surface temperature. Cooling then lowers local saturation vapor pressure and raises RH, prompting readjustment of water-vapor diffusion, adsorption and desorption, capillary liquid transport, and phase change. When these hourly perturbations recur, their effects accumulate over seasons and across the full year, redistributing sensible and latent heat transfer and ultimately changing mold risk when prolonged humidity overlaps with favorable temperature. ELR is therefore not simply an additional heat-flux boundary. Through radiative cooling, local humidification, internal moisture migration and energy redistribution, ELR can alter long-term biological durability. The indicators also respond over different timescales. Temperature responds first to the radiative balance; RH lags because moisture must redistribute; sensible and latent differences emerge through long-term accumulation; and the mold index integrates the combined temperature, humidity and exposure history. Extreme-period responses identify radiative overcooling and thermal–moisture phase differences, annual loads quantify cumulative consequences, and the mold index links hygrothermal history to durability.

Climate strongly modulates both the strength and the consequences of this pathway. Harbin's colder sky and longer winter nights produce stronger surface cooling, higher exterior RH and greater sensible loss; retained moisture can raise mold risk when temperatures become favorable. In Guangzhou, humid, cloudier conditions and strong solar gain weaken the representative hot-period temperature response, yet recurrent cooling increases annual latent transfer against a high moisture baseline. Sensible transfer, latent transfer, and mold risk all increase in Harbin; in Guangzhou, sensible transfer decreases while latent transfer and mold risk increase. These findings extend previous evidence on facade thermal and energy effects [23,24] and on errors associated with simplified radiation boundaries [29] by demonstrating a moisture-mediated durability response. Direct numerical comparisons remain limited by differences in climate, wall construction and radiation formulations.

Spatially, ELR effects attenuate from the exterior inward. P1 is most sensitive, P2 and P3 retain measurable responses, and P4 and P5 exhibit zero mold index under the present conditions. Exterior insulation therefore effectively buffers external radiative forcing, although near-exterior material interfaces still warrant attention. Differences in thermal resistance, vapor resistance and moisture-storage capacity among layers can also produce locally non-monotonic responses, so interface risk cannot be inferred solely from geometric depth. The main limitations of the present study arise from the simplified geometric and environmental boundary assumptions. The model represents the intact central region of a one-dimensional wall under standardized WDR conditions. Site-specific WDR redistribution associated with urban shielding, eaves and facade surface characteristics is not explicitly resolved, and longwave exchange is limited to the sky rather than represented through a complete radiation network involving neighboring buildings and the ground. Multidimensional features such as windows, corners and anchors, together with cracks and air leakage, are also excluded. The results should therefore be interpreted as relative ELR-induced response patterns for intact one-dimensional facade regions with substantial sky exposure. Their direct application to dense urban environments or envelopes with complex geometric details requires consideration of surrounding-surface radiation exchange and multidimensional heat and moisture transfer. Future studies should extend the present framework to two- and three-dimensional

building details and incorporate site-specific WDR distributions derived from field measurements or CFD. Multi-surface longwave exchange with neighboring buildings and the ground should also be considered in dense urban environments. In addition, multi-year and future-climate datasets, together with long-term field measurements of moisture and mold development, would help quantify climatic uncertainty and further evaluate the predicted mold-risk response.

For engineering applications, envelope design and durability assessment in severe-cold regions should account for ELR-induced surface overcooling, increased heat loss, and moisture accumulation. In hot-humid regions, moisture accumulation and mold risk should receive particular attention even when the transient thermal effect of ELR is relatively small. ELR should therefore be evaluated within a coupled hygrothermal framework, particularly at the exterior surface and near-exterior interfaces.

5. Conclusions

A transient HAMT model for building envelopes was developed using temperature and capillary pressure as the primary variables, with WDR, solar shortwave radiation, and dynamic sky longwave radiation represented jointly in the exterior boundary. Harbin and Guangzhou were used to represent severe-cold and hot-summer/warm-winter climates, respectively. The model quantified the effects of ELR on transient wall temperature and humidity, annual sensible and latent heat transfer, and mold-growth risk. The principal conclusions are as follows.

- (1) ELR effects on envelope hygrothermal response are strongly climate-dependent. Winter sky radiative cooling in Harbin lowers the minimum exterior-surface temperature and increases the through-wall temperature difference. Mean exterior-surface RH rises by approximately 9.1 percentage points, and its peak increases from 91.4% to 99.7%. In Guangzhou, high atmospheric humidity, cloud cover, and strong solar radiation produce much weaker transient thermal and moisture responses during representative hot periods.
- (2) Repeated ELR perturbations alter the annual partitioning of sensible and latent heat transfer. Annual sensible and latent transfer in Harbin increase by 7.88% and 3.33%, respectively, indicating greater heating-period heat loss and moisture transport. In Guangzhou, sensible transfer decreases by 11.99%, whereas latent transfer increases by 7.54%. In a hot-humid climate, ELR can reduce annual sensible heat transfer while increasing moisture migration and latent exchange; sensible heat alone therefore does not capture its overall hygrothermal effect.
- (3) ELR-induced humidification translates into long-term mold risk. The maximum exterior-surface mold index at P1 increases from 2.20 to 3.89 in Harbin, a relative rise of 76.8%, and from 3.69 to 4.27 in Guangzhou, a rise of 15.7%. Guangzhou has the higher climatic baseline risk, whereas Harbin is more sensitive to the treatment of the ELR boundary. Absolute risk and sensitivity to radiative cooling should therefore be evaluated separately.
- (4) ELR-induced hygrothermal perturbations attenuate markedly with wall depth. P1 is consistently the most sensitive location. Mold indices at P2 and P3 remain low but increase to varying degrees when ELR is included, whereas P4 and P5 remain at zero. Exterior insulation effectively buffers propagation into the wall but does not eliminate long-term moisture risk at the exposed surface and near-exterior material interfaces.

Dynamic sky longwave radiation can therefore influence envelope heat and moisture transfer and moisture safety through surface radiative cooling, local humidification, and internal moisture migration. Envelope assessments should consider ELR together

with sensible heat, latent heat, and mold risk while accounting for the climate dependence of cumulative effects. Under the assumptions of an intact one-dimensional facade, standardized WDR treatment, and TMY weather data, the results provide climate-specific comparative evidence for envelope assessment, durability evaluation, and energy retrofit rather than universal design prescriptions.

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