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Intrinsic Evaporative Cooling with Natural Ventilation and Shading for Adaptive Thermal Comfort in Tropical Buildings

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ABSTRACT

Hygroscopic materials, including earth- and plant-based materials used in tropical vernacular architecture, often sorb significant moisture from the atmosphere during humid nighttime hours; evaporation the following day then provides a pronounced cooling effect, particularly in semi-arid regions. While such intrinsic evaporative cooling is also active in wet-tropical climates, it cannot maintain indoor comfort, and vernacular structures are highly open to facilitate air movement. Recently, new hygroscopic materials have been developed from coconut agricultural wastes that show great potential for intrinsic evaporative cooling and indoor humidity control in contemporary tropical buildings. As expected, however, they must be combined with additional cooling strategies to maintain thermal comfort. This investigation explores the integration of intrinsic evaporative cooling with natural ventilation and shading to determine the extent to which indoor thermal comfort, as evaluated by the ASHRAE 55 adaptive thermal comfort standard, may be maintained in the representative wet-tropical climate of Ghana, West Africa.

KEYWORDS
intrinsic evaporative cooling, hygroscopic, agrowaste, natural ventilation, passive cooling

INTRODUCTION
Hygroscopic materials, including adobes, grasses, fibers, and leaves used widely in tropical vernacular buildings can sorb significant moisture from the atmosphere during humid nighttime hours; evaporation the following day can then offset appreciable solar gains. This phenomenon, termed intrinsic evaporative cooling, has recently been characterized in diverse earth materials and semi-arid climates (Rempel 2016) as well as in agrowaste fibers and fiberboards in humid and subtropical climates (Lokko 2016). Intrinsic evaporative cooling in itself, however, cannot maintain indoor comfort in humid tropical climates (Lokko 2016). While moisture sorption by hygroscopic agrofiber envelope materials has previously been shown to lower indoor humidity to as little as 70% of outdoor daytime levels (Lokko 2016), indoor operative temperatures remained outside adaptive thermal comfort standards (ASHRAE 2017) and higher than outdoor conditions. The present study addresses these comfort issues by incorporating the effects of shading and natural ventilation, using window operation strategies common in tropical cities like Accra, Ghana, and evaluating results in light of the adaptive comfort standard (ACS) to reflect the relaxation of thermal expectations and higher levels of perceived control observed in naturally ventilated buildings (Brager 1998). Following natural ventilation strategies used in vernacular and contemporary buildings, which facilitate air movement through occupied zones, this work studies the impact of shading and natural ventilation on two scales of window openings. While the ACS applies to sedentary activity and may not account for the changing thermal preferences of tropical building inhabitants who have become accustomed to air-conditioning, it is used here to reflect the broad thermal adaptation typical of people living in the tropics.

METHODS
A simple gabled rectangular building with multiple window and shading configurations was
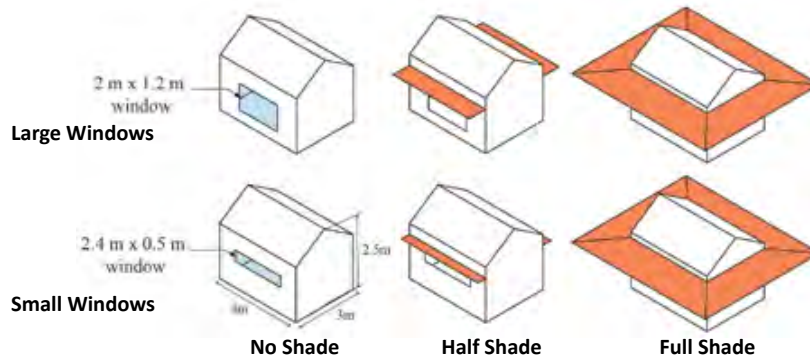
Figure 1. Study building dimensions, window configurations, and shading elements.

modeled in EnergyPlus 8.7, using Euclid 0.9.3 for geometry input (Fig. 1). Oriented along the east-west axis, the roof and walls were simulated as hygroscopically-active coconut fiberboard assemblies surrounding a tiled concrete floor in contact with the ground. Internal gains assumed a single occupant, with a sensible heat fraction of 0.3, activity level of 90-120 W/person when occupied, and 5pm-9am residential occupancy. To understand heat, air, and moisture transfer patterns, the EnergyPlus Heat and Moisture Transfer (HAMT) algorithm was used to simulate the effects of evaporation from, and condensation onto, building materials following established procedures (Rempel 2016). Infiltration and natural ventilation were simulated with airflow networks, allowing EnergyPlus to calculate wind pressure coefficients from the orientations of wall and roof surfaces with respect to wind speed and direction. Infiltration, active in all models, was governed by an air mass flow coefficient of 0.001 kg/s at reference conditions of 20°C with a cross-crack pressure difference of 1 atm, for wall and roof assemblies, and 0.01 kg/s at the same reference conditions for window perimeters, reflecting typical construction practices. Natural ventilation, in turn, assumed openable areas equal to the window areas specified (Fig. 1), with discharge coefficients estimated conservatively at 0.65. To reveal the effect of natural ventilation on indoor operative temperatures, independent of shading, models possessing either small or large windows (Fig. 1) were simulated with a baseline condition of closed windows (i.e. with infiltration only) and with two predominant ventilation control practices found in Ghana in the hottest months: one with windows open only during the day, and one with windows open both day and night. Natural ventilation was anticipated to improve thermal comfort in three ways: first, by removing warm indoor air and replacing it with cooler outdoor air; second, by cooling thermal mass; and third, by increasing indoor air velocity, thereby accelerating evaporation of moisture from skin and effectively expanding the thermal comfort zone. Because of this, building indoor operative temperatures (°C) and air velocities (m/s) were compared to adaptive comfort boundaries in each case. All simulations used the SWERA weather file for Accra, Ghana, and results were reported for one representative week in March, the warmest month of the year.

Table 1. EnergyPlus Model Parameters

Construction	Material	Density (kg/m³)	Thickness (m)	k (W/m-K)	c (J/kg-K)
Exterior Floor	Heavyweight concrete	2240	0.1016	1.95	900
	Ceramic tile	1920	0.0127	1.59	1260
Coconut Wall	Coconut Fiberboard	1100	0.00952	0.36	4379
Coconut Roof	Coconut Fiberboard	1100	0.00952	0.36	4379
	Coconut Fiber mat	155	0.00318	0.03	4102
Window Glazing	Clear uncoated glass	-	0.003	0.90	0

RESULTS

Intrinsic evaporative cooling. Typical outdoor air temperatures in Accra, Ghana in March, the warmest month of the year, fluctuate from the high 20's to low 30's Celsius, while outdoor relative humidity typically rises above 80% overnight but falls to ~60% at mid-day (Fig. 2a). Sorption of moisture from humid nighttime air by hygroscopic coconut fiber materials is evident in latent heat transfer into wall and roof surfaces, shown by negative values. Evaporation from these surfaces, in turn, which provides cooling, is shown by positive latent heat flux values, resulting in an average daytime evaporative cooling effect of ~50 W/m² for wall and ~15 W/m² for roof surfaces. While this process effectively diminished indoor relative humidity compared to outdoor levels (Fig. 2a), indoor temperatures remained uncomfortably high (e.g. Figs. 3a, c).
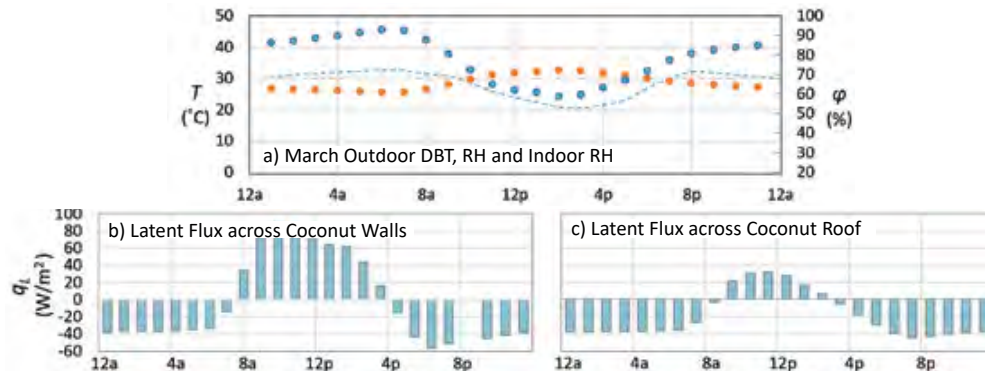

Figure 2. Intrinsic evaporative cooling in the study building, showing a) March outdoor air temperatures (orange dots) and relative humidities (blue dots) and indoor relative humidity (blue dashes), as well as latent heat fluxes across b) coconut fiberboard walls and c) roof surfaces.

Natural ventilation. Without natural ventilation, i.e. with only infiltration to exchange indoor and outdoor air, indoor operative temperatures reached ~40°C at mid-day, with small-windowed models remaining only slightly cooler than the large-windowed counterparts (Figs. 3a,c). This shows the importance of heat transfer through the lightweight, relatively conductive coconut envelope panels, which contributed more than window solar transmission or infiltration to total heat gain. At the same time, this envelope allowed "No Vent" models to cool to near-outdoor temperatures each night, such that near-comfortable conditions were predicted during most occupied hours (6pm-8am). Adding daytime ventilation (8am-8pm) diminished daytime operative temperatures dramatically, lowering peak values by about 6°C in the days shown (Fig. 4) and bringing 2-4 additional hours per day into the adaptive comfort zone, easily encompassing the occupied hours. Night operative temperatures dropped as well, though less extensively, reaching minima ~1-2°C lower than observed in "No Vent" models. This drop was associated with lower mass surface temperatures, showing that the limited mass provided (0.5cm ceramic tile over a 10cm concrete floor) was able both to sustain higher nighttime temperatures when ventilation was eliminated, and to facilitate additional cooling when it was permitted, even during the day. Adding night ventilation, i.e. opening windows for 24h daily, did not noticeably affect indoor operative temperatures in either small- or large-windowed models (Figs. 3a, c). This was unexpected, given the massive floor, but closer inspection revealed several explanations. First, March nighttime winds are typically low in Accra (≤3 m/s in >90% of hours), compared to daytime values of 4-6 m/s, diminishing night ventilation' effectiveness. Second, infiltration exchanged sufficient air at night in the "12h Vent" model that open windows added only modest air exchange. Third, consistent with the previous two points, the mass floor did not become appreciably cooler in the "24h Vent" models, showing that the additional air exchange was not enough to lower floor mass temperatures to an extent relevant to thermal comfort.
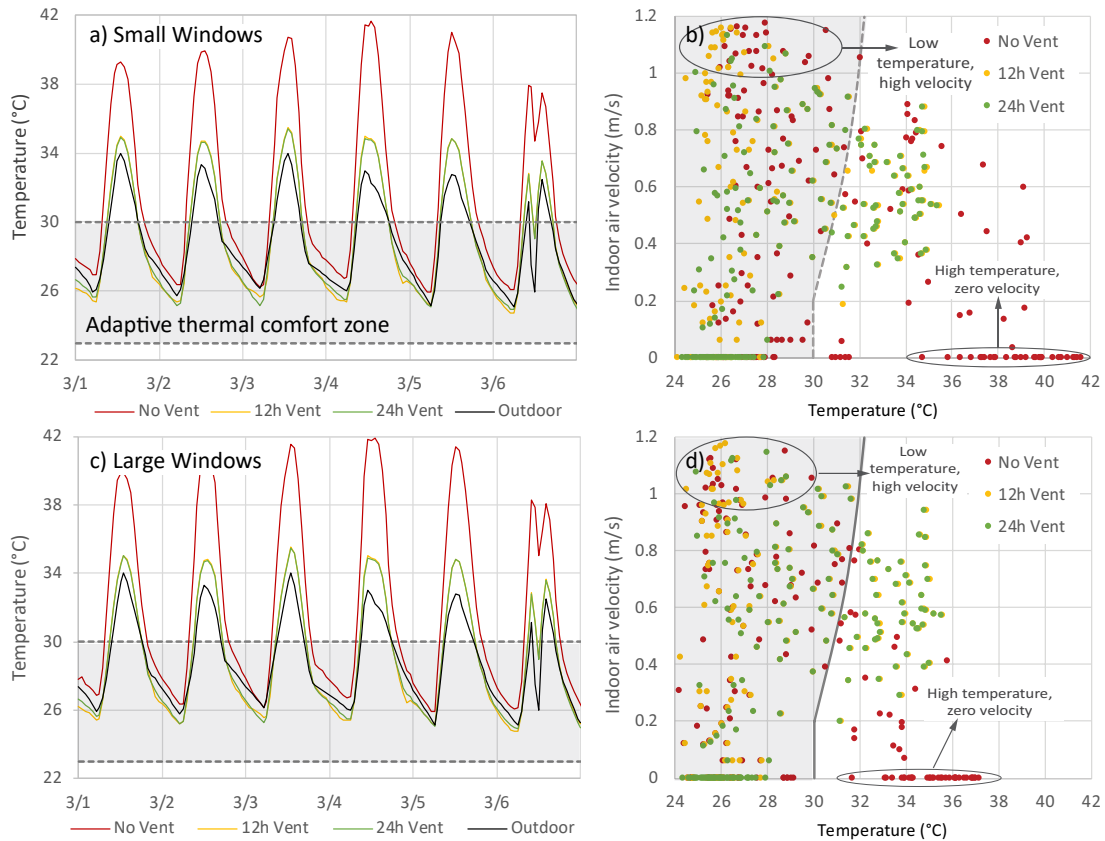
Figure 3. The predicted   natural ventilation alone on indoor operative temperatures and adaptive thermal comfort (shaded areas) over six representative March days in Accra, Ghana, for dwellings with small (a, b) and large (c, d) window   Vent":
"12h Vent": windows open 8am-8pm; "24h Vent": windows open at all times.

To reveal whether increased air velocity brought some of the warm hours into the velocity- expanded comfort zone (ASHRAE, 2017), air velocity was next plotted against operative temperature (Figs. 3b, d). "No Vent" models predicted considerable indoor air motion from infiltration; this was calculated as a function of pressure difference across each crack, which is a function of both temperature difference and wind pressure (USDOE, 2016), with the result that high indoor air temperatures drove considerable exfiltration (coinciding with calm indoor air, shown as pronounced rows of high-temperature, zero-velocity symbols (Fig. 3). Adding daytime ventilation ("12h Vent") replaced this hot-hour exfiltration with cooler air of considerably higher velocity, allowing thirteen hours with operative temperatures >30 °C to enter the velocity-expanded comfort zone over a six-day period, or ~2h per day. Adding all-day ventilation ("24h Vent") had little effect on daytime conditions, as expected, but diminished the bursts of infiltration-driven high air velocity that occurred during the coolest hours of the night in the previous two models, replacing them with steadier, lower-velocity air movement.

Shading. The cooling effect of shading alone was investigated by comparing a configuration with no shade at all ("No Shade") with two having external overhangs that shaded half or all of the south-facing wall at noon, including the entire south-facing window in both cases ("Half Shade" and "Full Shade", respectively). As expected, shading noticeably lowered indoor temperatures: while unshaded models reached peak operative temperatures of ~40°C on typical March days (Fig. 4), far beyond the thermal comfort range, half-shading reduced these peaks by 1-1.5°C, and full shading reduced them by 2-3°C, providing significant cooling given the un-

shaded, relatively conductive roof. Shading alone did not, however, bring additional hours into the adaptive comfort zone (Fig. 4), showing that further cooling measures would be necessary.
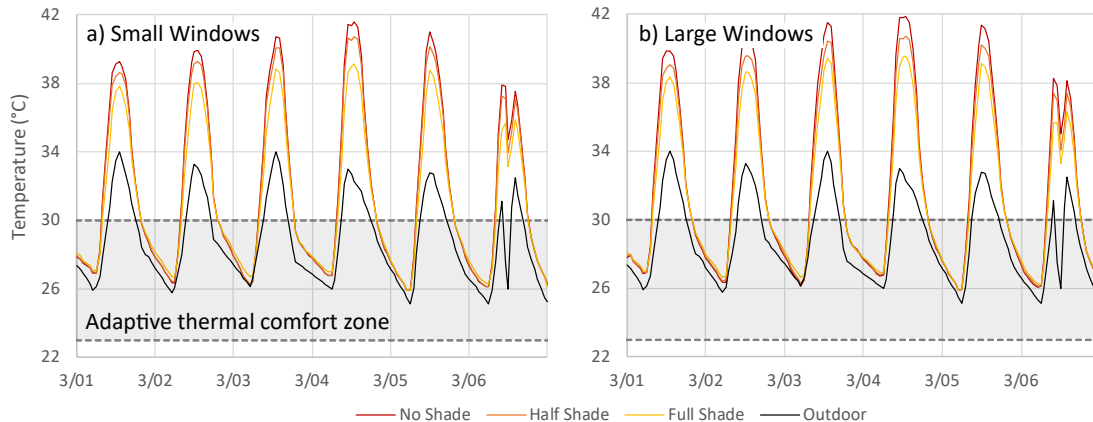

Figure 4. The predicted effect of shading alone (i.e. without natural ventilation, apart from infiltration) on indoor operative temperatures and adaptive thermal comfort (shaded areas) in six representative March days in Accra, Ghana, for dwellings with small (a) and large (b) window configurations. "No Shade": windows are unshaded at all times; "Half Shade": walls are half shaded at noon by exterior overhangs; "Full Shade": walls are fully shaded at noon by exterior overhangs.

Combinations. Since shading showed cooling ability independent of natural ventilation, combinations of "12h Vent" and "24h Vent" with "Half Shade" and "Full Shade" were next investigated. As expected, these out-performed each individual strategy, reducing peak operative temperatures by ~1°C each day in both small- and large-windowed models (Figs. 5a, c) and bringing them to within 1°C of the outside air temperature. They did not, however, cool additional hours below the 30°C threshold of the adaptive comfort zone; instead, additional cooling appeared confined to the warmest hours of the day. Furthermore, shading did not improve the ability of natural ventilation to bring additional hours into the comfort zone through air velocity; 12-14 warm hours were made comfortable by air movement regardless of shading level (Figs. 5b, d).

DISCUSSION
While building simulations are vulnerable to numerous sources of error, including algorithmic simplifications (USDOE, 2016), failure to capture occupant usage patterns accurately, etc., they are invaluable for revealing priorities for subsequent investigations. In this study, the modest effect of wall and window shading, combined with high heat gains through the roof, revealed the likely importance of ventilated attics that allow roofs to shade interior ceilings in such lightweight construction. Likewise, the ability of cross ventilation to expand the hours of adaptive comfort by two per day through increased air velocity suggests a valuable resource worthy of field investigation; thermal mass configurations were similarly shown to be in need of further study in this climate, with little diurnal temperature variation, given the nearly identical results generated by 12h and 24h ventilation patterns. Finally, any interdependence among intrinsic evaporative cooling, shading, and natural ventilation remains mysterious, although interaction is likely: a shaded wall is expected to evaporate less moisture, for example, while a naturally-ventilated interior might evaporate more.

CONCLUSIONS
Together, shading and natural ventilation, in the most effective combinations, lowered predicted indoor operative temperatures in the coconut-material study building from peak levels that exceeded outdoor temperatures by ~10°C to levels approximating outdoor temperatures.
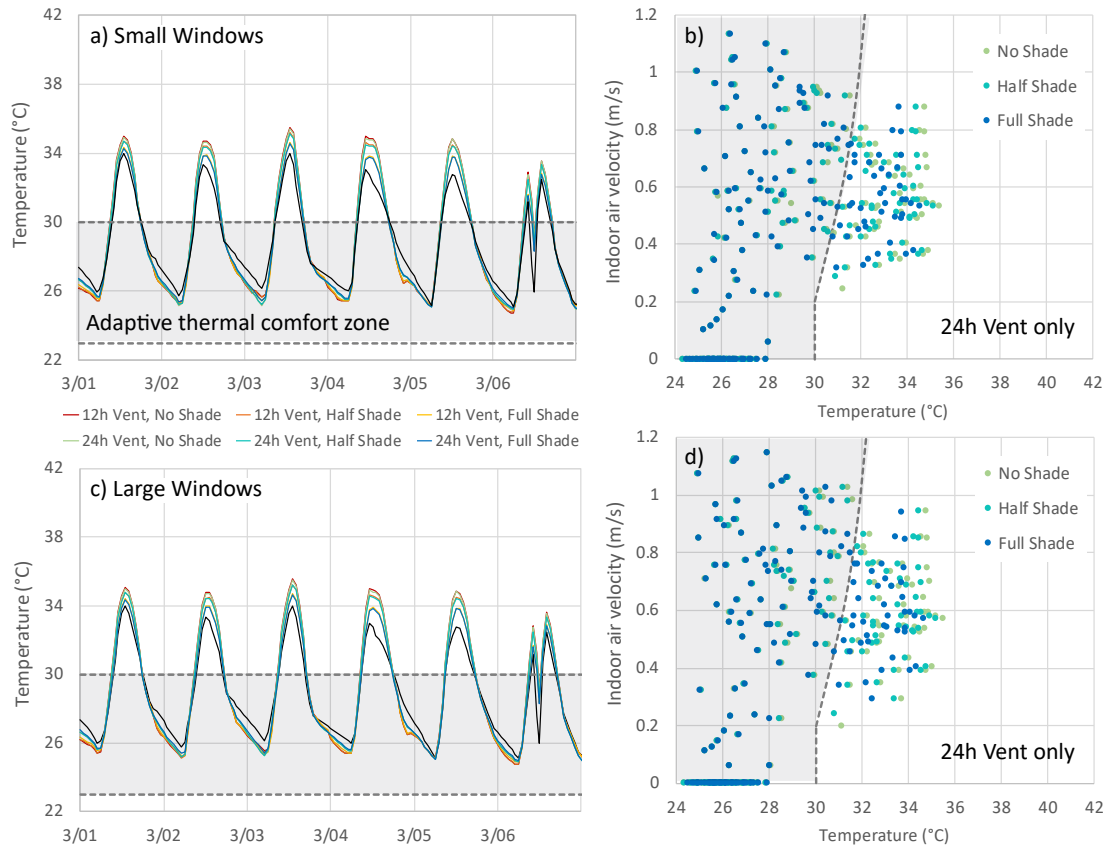
Figure 5. Predicted effects of combined shading and natural ventilation on adaptive thermal comfort (shaded) in March in Accra, Ghana, for dwellings with small (a, b) and large (c, d) window configurations. "No Shade": unshaded at all times; "Half Shade": walls half shaded at noon by exterior overhangs; "Full Shade": walls fully shaded at noon by exterior overhangs; "No Vent": infiltration only; "12h Vent": windows open 8am-8pm; "24h Vent": windows open at all times.

While further cooling is necessary for daytime comfort, this represents significant p rogress. The upcycling of local agricultural waste such as coconut husk into building materials has the potential to expand the economic value chain of coconut producers in tropical nations while producing low-embodied energy materials. Because of this, further investigations of their effective integration into buildings, allowing them to provide reliable thermal comfort without energy-intensive mechanical air conditioning, hold economic, environmental and social value.

ACKNOWLEDGEMENTS

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