Incorporating Courtyards as a Sustainable Design in Vernacular Architecture to Decrease Energy Use and Increase Thermal Comfort

By
Autumn Blaisdell
Department of Environmental Science
Allegheny College
Meadville, Pennsylvania

April, 2021

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Autumn Blaisdell
Department of Environmental Science
Allegheny College
Meadville, Pennsylvania

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Submitted in fulfillment of the senior thesis requirements of the
Department of Environmental Science at Allegheny College
and approved by the senior thesis committee.



_____	__4 May 2021_____	_____	_____
Dr. Brittany Davis	Date	Dr. Ian Carbone	Date

Autumn Blaisdell
Pledge

Name: Autumn Blaisdell Date: Spring, 2021
Major: Environmental Science and Sustainability
Thesis Committee: Dr. Brittany Davis, Dr. Ian Carbone

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Abstract

Courtyards have been around for millennia operating as microclimate modifiers before fossil fuel-based cooling technologies began dominating worldwide energy consumption. The main goal of this study investigates the implications of reintroducing courtyards and its accompanying strategies into vernacular architecture as a passive sustainable design that aims at decreasing energy use and increasing thermal comfort. As a descriptive-analytic study, the literature review for this paper focuses on peer-reviewed articles on successful designs of courtyards in hot-arid and tropical climates, climatic responsive designs and passive energy solutions in order to demonstrate that appropriately designed courtyards are legitimate architecture that can decrease energy use and increase thermal comfort. Studies on courtyards and its accompanying strategies such as passive cooling and heat mitigation techniques were analyzed, and their results observed. The results presented that instituting climate-appropriate designs such as vegetation, dimension rations, natural ventilation, wall type and orientation of courtyards into buildings decreases energy use and increases thermal comfort. From successful courtyard designs, this study will interpret incorporating courtyards into homes and neighborhoods in the tropical savannah microclimate of Kapolei, O`ahu. Also, this study aims to add knowledge of the energy efficiency of courtyards to the field of sustainable development.

Keywords: vernacular architecture, courtyards, passive cooling, energy usage, Hawai`i, O`ahu, climatic responsive design, thermal comfort

Acknowledgements

I want to give a shout out to 302 Loomis for keeping it real and holding it down with me. I want to thank Mikayla AhSam for supporting me through the wild ride of my senior year. And I want to give special thanks to Maryjane for settling my anxiety and helping me coast through this entire process.

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0.0: Introduction

Building energy use accounts for 40% of primary energy consumption in the US and the EU (Cao et al., 2016). As population exponentially increases so does the need for residential buildings that require energy-intensive heating and cooling (Motealleh et al., 2018). On O`ahu, Hawai`i urbanization rates are steadily increasing, such as in Kapolei, where the city's population growth rate in 2018 was 1.84% (Data USA, n.d.). Presently, climate change is being exacerbated by the myriad of energy-intensive buildings being constructed. To combat this, sustainable development can be used because its overarching goal is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Emas, 2015) and has been an emerging field that seeks to decrease carbon emissions by decreasing energy usage in homes.

Vernacular architecture is described "as an architecture that respects and adapts to the physical and technological limitations of its context, raised as the genuine result of its environment, its people and its history" (Ghisleni and Duduch, 2020). Meaning that by tailoring the architecture to the surrounding environment and acknowledging the physiological and psychological needs of its inhabitants, vernacular architecture can be a viable outlet for sustainable, energy-conscience home development designs. Courtyards are a viable and successful vernacular architecture design element that capitalizes on passive cooling in order to decrease energy use and improve indoor thermal comfort ([1]Soflaei et al., 2017; [2]Soflaei et al., 2020; Nugroho et al., 2020; Rodríquez-Algeciras et al., 2018; Bulus et al., 2017). Courtyards are historically square or rectangular, enclosed by four walls, are open to the sky, and emphasize the relationship between regional climate, architecture and inhabitants (Mohammad, 2020). Understanding the relationship between those factors allows for courtyards to be tailored to climates all over the globe, especially harsh climates that would normally call for an extensive use of energy-intensive cooling technologies ([1]Soflaei et al., 2017; [2]Soflaei et al., 2020; Nugroho et al., 2020; Rodríquez- Algeciras et al., 2018). Contemporary architecture can utilize climate specific solutions and locally produced resources and incorporate cultural aspects into courtyards to provide inhabitants with optimal and preferred living conditions that are energy efficient ([3]Soflaei et al., 2016; Motealleh et al., 2018).

This study explores climate specific courtyard designs from case studies in hot-arid and tropical climates in order to prove that those designs can be applied to Kapolei, Hawai`i's tropical

savannah climate in order to decrease energy use and increase indoor thermal comfort. The designs include natural ventilation, vegetation, wall material, dimension ratios (height to width ratio), and orientation within and of courtyards. The designs from the case studies are analyzed for successful design variables and then applied to courtyards in Kapolei, Hawai`i to prove that courtyards can be a viable and successful design. Urban development in Kapolei, Hawai`i is steadily expanding creating a growing need for knowledge about passive cooling within vernacular architecture. Hopefully, this study can bring attention to the aspect of climate specific and sustainable development strategies within urban development in order to decrease building energy usage and to offer courtyards as a part of that development and design.

0.1: The Context of Hawai`i

Kapolei, O`ahu, Hawai`i was chosen for this study because of the city's steadily expanding population and urban development. In the 2010 US census, Kapolei had a population of 15,186 (US Census Bureau, 2010) which dropped down to 13,300 in 2013 and, now, in 2021, the total population is just under 21,700 (World Population Review, n.d.). Over the last decade, urban expansion has led to the increase of energy-intensive buildings, especially for the city's hot, semi-arid climate (Climate Data Org, n.d.) because of buildings' dependency on energy-intensive cooling technologies. Kapolei is more likely to use more energy per household compared to other climates that may be naturally cooler, thus showing that climate is an important factor when it comes to the success rates of courtyards within vernacular architecture. The climate of Kapolei is considered a hot semi-arid (steppe) climate, a BSh on the Köppen-Geiger climate classification code (Climate Data Org, n.d.; Climate Data Org, n.d.), which is an intermediary between hot climates and humid climates. The BSh climate is also known as a tropical savannah. The average temperature in Kapolei is 23.9 degrees C/ 75 degrees F and the city receives 354 mm/ 13.9 inches of rain annually on average (Climate Data Org, n.d.). Honolulu County, which Kapolei is a part of, receives 271 days a year of sun (Current Results, n.d.).

Figure 0.1.a: Kapolei, Hawai`i Urban Density



Credit: Civil Beat Honolulu

Figure 1: An ariel view of most of the city of Kapolei, Hawai`i in 2016 shows the expansion and urbanization of the city.

0.2: History of Courtyards

Historically and traditionally, courtyards provided a private space that connected the inhabitants with the outdoors and for familial use and gatherings, assisted cultural and religious practices, and acted as a microclimate modifier, especially for dwellings located in harsh climates (Abass et al., 2016; Mishra, 2016). Before energy-intensive climate modifiers, such as air conditioning came about, vernacular architecture such as homes, incorporated courtyards as a microclimate modifier to stabilize temperature swings throughout the day. The term microclimate modifier means that the climate surrounding and located within the house can be semi-controlled through the means of a courtyard in order to create a space that is thermally comfortable for its inhabitants (Zamani et al., 2018). Courtyards have been around for millennium with some of the oldest courtyards being developed in India and China in 6500-6000 BC (Mishra, 2016) and other ancient civilizations across North Africa to China ([2]Taleghani et al., 2012). Over the millennium, classical civilizations also employed courtyards for thermal comfort, the middle ages sought to

add cultural benefits, and the modern era finally saw the expansion of the use of courtyards to the west of North America (Zamani et al., 2018).

Along with physical and cultural benefits of courtyards, religion has played a large role in the usage of courtyards, especially in Arab cultures where the dominant religion is Islam. The separation between gender within religions has affected how courtyards are applied in those local contexts. For example, in religions where a woman's privacy is utmost important, a private courtyard laid in the interior of the home allowed for women to enjoy outdoor spaces and leisure activities with privacy and for familial use (Mishra, 2016). Additionally, another, smaller courtyard would be located near the entry of the house that the men of the house and the guests would use (Mishra, 2016). Religion has influenced the construction and use of courtyards and at the same time has sustained "gender segregation and a strict social hierarchy" in particular contexts (Mishra, 2016).

With the globalization and mixing of populations and cultures, the design of courtyards transformed from traditional topologies (which varied depending on location; see Abass et al., 2016) to amalgamated structures that intermingled multicultural designs and brought about new social expressions (Mishra, 2016). Albeit we must realize that these changes were heavily influenced by colonialization and were not always welcomed. This is alluded to by Mishra (2016) who says that when the British colonized India they brought with them their "families, culture, religion, social values, and architecture." Across the globe, transmigration and colonization brought about a metamorphosis of local architecture. Leading up the modern era, the prevalence of courtyards has decreased significantly. Mishra (2016) describes five reasons for the disappearance of courtyards: greater concern for image of house rather than the integration of spaces within it, individualization of rooms, change from joint to nuclear families, housing policies of smaller land plots, and housing development changing form horizontal to vertical development. Contemporarily, courtyards have found a balance between thermal comfort, energy usage and cultural aspects that have sparked their resurgence in vernacular architecture. And because of this, courtyards can be a viable and successful design that seeks to decrease energy usage within urban development in Hawai`i.

Figure 0.2.a: Traditional Iranian Courtyards



Credit: Friendlyiran.com

Figure 1: Featuring geographically specific vegetation, high aspect ratios, and water pools, traditional Iranian courtyards show how courtyard architecture is incorporated into buildings to stabilize harsh climate conditions.

0.3: Climatic Responsive Solutions

Courtyards are a sustainable design strategy that provides vernacular architecture with a higher rate of thermally comfortable indoor and outdoor environments that can be enjoyed by its inhabitants (Motealleh et al., 2018). Climatic responsive solutions simply are design variants of courtyards that can be manipulated in order to affect the success of the courtyards ability to reduce energy consumption and increase thermal comfort. This study looks at the broad climatic responsive solution of passive cooling. Passive cooling provides thermally comfortable environments by implementing heat reducers such as heat prevention, heat modulation, and heat dissipation, and in this paper, these will be generalized under the term, heat mitigation (Mohammad, 2020). Specific climatic responsive solutions included in this study is natural ventilation, vegetation, wall type, dimension ratios (height to width ratio), and orientation.

Natural ventilation takes advantage of air pressure differences in and around the courtyard to create air flow within the building; cross ventilation to greatly reduce high temperatures and stabilize cooler night temperatures. Vegetation will be used to absorb daytime heat and to enhance air moisture to cool down the surrounding area (Bulus et al., 2017). Wall material acts as a thermal lag – where walls absorb daytime heat and release it during the night in order to minimize heat gain during the day and to stabilize night temperatures. Ratios affect the cooling effect of the courtyard - narrower and taller dimensions lend cooler temperatures because they provide shading and minimize heat gain during the summer months ([2]Taleghani et al., 2012). And orientation enhances natural wind flow and minimizes sunlight exposure during the summer and maximizes it during the winter for greater thermal comfort year-round.

To receive the greatest passive cooling and heat mitigation benefits, as many rooms of the house as possible should border the courtyard because the cooler air located within will disperse to the surrounding area, keeping daily temperatures lower than average and keeping nighttime temperatures stable. Although climatic responsive designs are highly dependent on the local climate, they can prove to be amazing solutions if incorporated properly, creating a viable and successful architecture design that can increase thermal comfort and decrease energy use.

1: Methods

With the onset of climate change affecting the globe, the Islands of Hawai`i are especially susceptible to climate change effects making it an important place to study and apply sustainable designs that aim to decrease energy usage. This research ultimately intends to find a successful courtyard design for Kapolei, Hawai`i in order to decrease energy that is consumed in vernacular architecture. Methods for this paper are heavily guided by a descriptive-analytic literature review.

First, the relationship between architecture, energy consumption and sustainability were explored to find an architectural design that decreased energy consumption. Through initial research, the terms passive energy design and courtyards became prevalent in tandem in papers. The use of courtyards as a passive cooling technology was the result. Keywords of initial searches included: courtyards, energy consumption, vernacular architecture, and sustainability.

Second, the selection of locations for case studies were sought by exploring papers that had a plethora of research and simulation-modeling for their climate. Hot-arid and tropical climates were the top two. Search terms for these included hot-dry climate, hot-humid climate, traditional Iranian courtyards, Malaysia, and China. These case studies are vital to the process of discovering successful courtyard designs from unsuccessful ones. Moreover, each case study was analyzed for successful climatic responsive solutions and energy savings post courtyard construction. In the end, Cuba and Indonesia were found through research on tropical climates, and Iran and Arizona were found for hot-arid climates, and thus selected for the case studies because the locations overlapped the aspects of the tropical savannah of Kapolei, Hawai`i.

Third, selecting the tropical savannah microclimate of Hawai`i accomplished two things: it encompassed aspects from both of the broader climates, and represented a location on O`ahu, Hawai`i where urban development is expanding rapidly. Kapolei is an up-and-coming city that needs sustainable development to lead the steady urban development that is occurring. Lastly, conclusions are drawn to determine if courtyards will be applicable to O`ahu.

The focus of this study is not only to prove that courtyards are successful in decreasing energy usage but to also explore new possibilities in sustainable development that can be applied to urban development in a period of irreversible climate change. Therefore, this research will provide vital insights to the concern of dealing with a rapidly expanding population and how to address the energy-intensive needs of that population. As with Kapolei, the city makes for a perfect

case to apply courtyards to because of high energy dependency. The developers and communities of Hawai`i alike need to realize all the renewable resources that are at their disposal in order to adapt to a changing climate.

2: Cast Studies on Courtyards in Hot-arid Climates

Subtropical desert climates largely occur in the Middle East, the middle of Australia and North Africa because moisture-laden air rarely makes its way to the interior of continents leaving the arears devoid of precipitation (Britannica, 2016). The Sonoran Desert of North America, the Atacama Deserts of South America, and the western part of the Sahara Desert all represent tropical and subtropical deserts or hot-arid climates (Britannica, 2016). Subtropical deserts receive between 0 – 10 inches/ 0 – 25 cm of precipitation a year, have high daily temperatures and wide daily temperature variations, and frequently have cloudless days (Britannica, 2016). This means that the days are extremely hot while night temperatures usually drop to 40 degrees F less than midday temperatures (Britannica, 2016). These factors are perfect for creating hot and arid conditions.

This section will analyze two case studies of courtyard designs from hot-arid climates of Yazd, Iran and Phoenix, Arizona, USA in order to extrapolate climatic responsive solutions that use passive cooling to decrease energy usage and increase indoor thermal comfortability. Courtyards in these climates emphasize the importance of length to height ratios and wall type for creating passive day cooling and comfortable nighttime temperatures ([1]Soflaei et al., 2017; [2]Soflaei et al., 2020).

2.1: Yazd, Iran

Traditional courtyards in Iran have become an intersection of "experience and innovation, climate influence, Muslim lifestyles and traditions" ([1]Soflaei et al., 2017). Although there are many designs that courtyards embody, general houses have two square or rectangular courtyards: an external and an inner courtyard used to create comfortable temperatures and for religious values ([1]Soflaei et al., 2017). In Iran, the hot-arid climate covers two-thirds of the country ([1]Soflaei et al., 2017). Paired with high annual average sunlight hours, traditional Iranian architecture developed to have narrow alleys that reduce sunlight exposure and to orient buildings to take advantage of favorable winds to lower daily temperatures within the city and buildings ([1]Soflaei et al., 2017). With eight thousand years of evidence of buildings with courtyards, ([1]Soflaei et al., 2017) traditional Iranian architecture can offer successful courtyard designs that focus on orientation of buildings and height to width ratios of courtyards

2.1.1: Climate Classification of Yazd, Iran: Subtropical desert

The city of Yazd has a microclimate that represents a subtropical desert; a low-altitude, an arid, hot climate, and has an annual average temperature of 66.4 degrees F / 19.1 degrees C and a total annual average precipitation of 2.4 inches/ 61 mm ([1]Soflaei et al., 2017). On average, Yazd has 12 daylight hours per day and has an annual average relative humidity of 31.5% (ClimaTemps, n.d.).

2.1.2: Successful Climatic Responsive Designs

Through a socio-environmental sustainability approach, [1]Soflaei et al. (2017) conducted a literature review and a field study in order to analyze various features of traditional courtyard houses in Iran to determine if particular designs can save energy and enhance social values ([1]Soflaei et al., 2017). This case study analyzed the five climatic responsive designs of orientation, wall type, dimension ratios, natural ventilation, and passive cooling ([1]Soflaei et al., 2017). It also included site specific floor type as influenced by local natural resources ([1]Soflaei et al., 2017).

2.1.2.1: Orientation

A north-south orientation is preferred for the locale because it maximizes solar impact during the winter months while minimizing solar impact during the summer months ([1]Soflaei et al., 2017). With this orientation, the south wall of the courtyard will provide the most shade throughout the entire year ([1]Soflaei et al., 2017), meaning that the southern part of the courtyard will garner much utilization. Taking advantage of the cool temperatures, courtyards might have gathering rooms on the southern side so thermal comfort can be achieved throughout the summer months during daily activities ([1]Soflaei et al., 2017).

2.1.2.2: Wall Type

Homogenous and thick wall types have high thermal inertia which ensures cool temperatures within the house ([1]Soflaei et al., 2017). Thermal inertia is the ability of walls to absorb hot or cold temperatures on one side and release it on the other side of the wall. For example, heat absorbed during the day on the exterior of the courtyard will move slowly throughout the wall during the day and will release the heat during the night in the interior of the courtyard. Heat transfer like this can also be called time lag. This design allows for high daytime and low nighttime temperatures to be stabilized for greater thermal comfort. Implementing local natural resources such as bricks for wall type will harness time lag's slow heat transfer to keep indoor temperatures cool and allow for less temperature fluctuation ([1]Soflaei et al., 2017).

2.1.2.3: Dimension Ratios

Dimensions between height and width play an important role in hot climates ([1]Soflaei et al., 2017). In Yazd, the city is built with narrow alleyways that channel winds and provide shade during the summer ([1]Soflaei et al., 2017). Similar with courtyards, dimensions are narrow enough to minimize direct solar impact in the summer but wide enough to have solar impact during the winter ([1]Soflaei et al., 2017). Additionally, traditional Iranian houses are usually two stories tall to shade the courtyard until the sun is right above the courtyard ([1]Soflaei et al., 2017).

2.1.2.4: Natural Ventilation

Since traditional Iranian houses generally don't have windows to the outside atmosphere (because of religious values), wind catchers are constructed on the south side of the courtyard to provide direct and indirect cooling to the courtyard ([1]Soflaei et al., 2017). Passive cooling happens when the wind catcher brings outdoor air into the courtyard and disperses it, creating a cross ventilation that lowers relative indoor air temperatures and increases thermal comfort ([1]Soflaei et al., 2017).

2.1.2.5: Vegetation

[1]Soflaei et al. (2017) referenced sources of successful uses of vegetation within courtyards. These two design variables increase the levels of air moisture in the courtyard and paired with shade from the vegetation, this combination keeps the air cool for its inhabitants ([1]Soflaei et al., 2017).

2.2: Phoenix, Arizona, USA

[2]Soflaei et al. (2020) covers the basis of contemporary courtyards in America over the last 30 years saying that their bioclimatic efficiency is underrated yet making a comeback within modern architecture ([2]Soflaei et al., 2020). Although the courtyard is not always a preferred design of architecture, it has proven to be viable and successful within modern construction ([2]Soflaei et al., 2020). [2]Soflaei et al. (2020) discusses the adaptive model invoked by courtyards, and the model assumes that occupants can act in certain ways to restore their comfort by adapting themselves and their environment to their needs ([2]Soflaei et al., 2020). The analysis of this case study will cover orientation, geometry and materials.

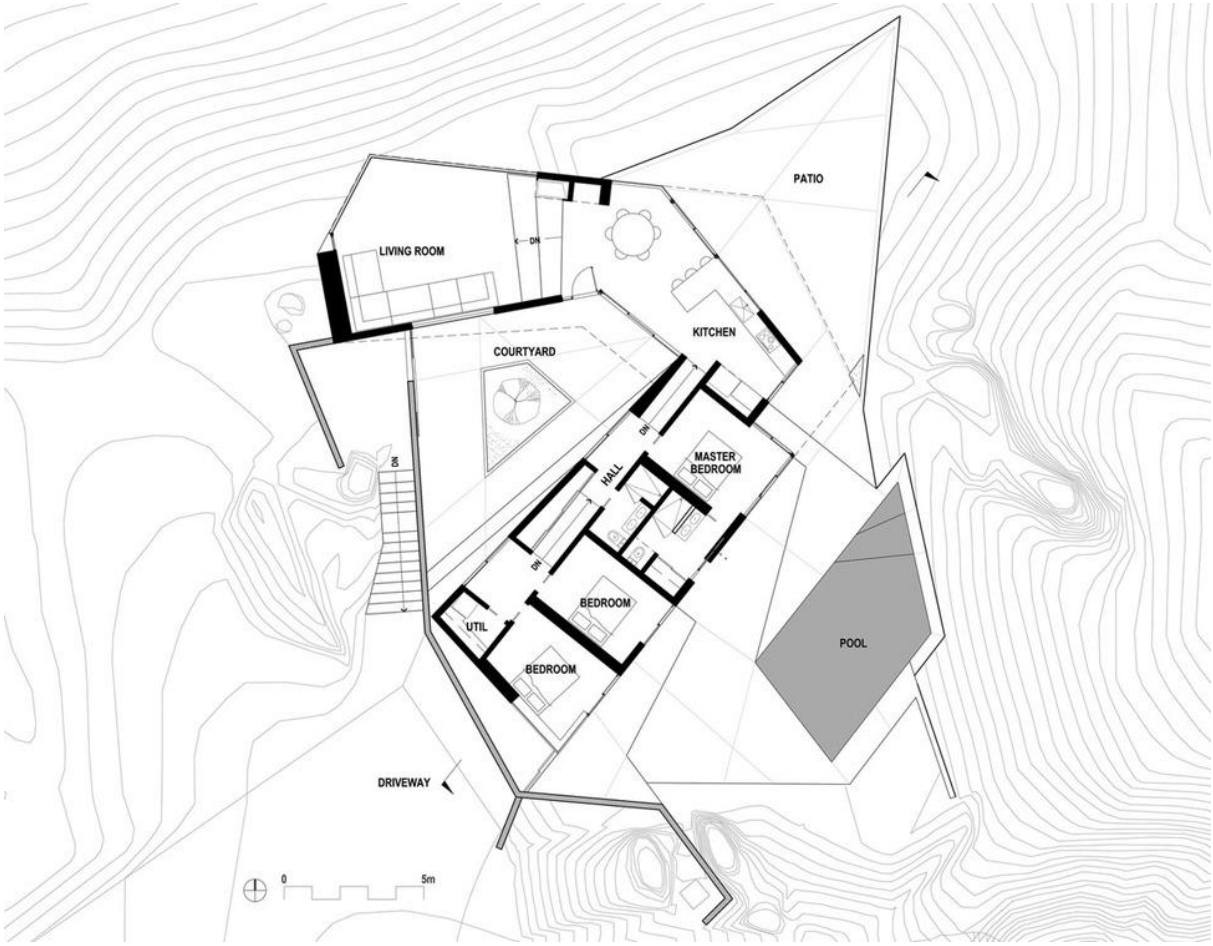
Figure 2.2.a: Contemporary Desert Courtyard House



Credit: Trendir.com

Figure 2.2.a: This house is based in Joshua Tree National Park and uses a courtyard as an aesthetic and functional aspect of the home.

Figure 2.2.b: Layout Design of Contemporary Desert Courtyard House



Credit: Trendir.com

Figure 2.2.b: Here, the courtyard is a central feature of the house that has many rooms bordering it. This maximizes air flow through the rooms to decrease air temperatures.

2.2.1: Climate Classification of Phoenix, Arizona, USA: Subtropical Desert

The state of Arizona can be divided into three main climates: half of the state is semi-arid, one-third is arid, and the remainder is humid (Britannica, n.d.). Days in January receive four-fifths of the possible sunshine with a mean average temperature of 65 degrees F/ 18 degrees C, while

July temperatures average at 106 degrees F/ 41 degrees C and the month receives on average 1 in/ 25 mm of precipitation. Phoenix, Arizona represents the subtropical desert microclimate of the south-western United States (Britannica, n.d.). Yearly climate is comprised of long and extremely hot summers and short mild to warm winters ([2]Soflaei et al., 2020). The city's annual average rain fall is 258 mm/ 10.2 inches per year, and its annual average temperature is 23.3 degrees C/ 73.7 degrees F ([2]Soflaei et al., 2020; Climate Data Org, n.d.). Although the average annual temperature seems mild, Phoenix is in one of the hottest cities in the US with an average of 107 days that reach at least 38 degrees C/ 100.4 degrees F and 300 days of sunshine ([2]Soflaei et al., 2020).

2.2.2: Successful Climatic Responsive Designs

[2]Soflaei et al. (2020) uses simulation-based modeling from the tool Grasshopper for parametric studies to investigate the impact on thermal comfort from design variables such as orientation, geometry, materials, window sizes, and eccentricity ([2]Soflaei et al., 2020). From the results of [2]Soflaei et al. (2020), 8600 design variations were simulated, and the best-case courtyard scenario will be discussed below. Overall, thermal comfort increased by 39.3% from base simulations by applying the best-case scenario solutions ([2]Soflaei et al., 2020). The other climatic responsive designs of natural ventilation and vegetation will be discussed in section 2.3.

2.2.2.1: Dimension Ratios

According to [2]Soflael et al. (2020), ratios as a stand-alone factor play a greater role than other factors for increasing thermal comfort. The best-case scenario for ratios for courtyards to increase thermal comfort as assessed by the simulation modeling is 9 m long by 6 m wide by 9 m high, or a 1.5 x 1 x 1.5 ratio ([2]Soflaei et al., 2020). Higher aspect ratios minimize direct solar radiation onto the courtyard and keep the air temperatures cooler for longer.

2.2.2.2: Orientation

For this case study, zero rotation orientation maximizes thermal comfort through passive cooling ([2]Soflaei et al., 2020). Increasing rotation to 90 degrees decreases thermal comfort by 9.7% ([2]Soflaei et al., 2020). This means that orientating it away from the N-S axis will decrease the

courtyard's success rate. Albeit the importance of orientation, dimension ratios are proven to be even more influential when it comes to thermal comfortability. To be sure though, zero rotation yielded the most thermal comfort for every simulation, but the orientation becomes more significant when height is also being manipulated ([2]Soflaei et al., 2020). The same relationship goes for when the wall type of the courtyard is being manipulated ([2]Soflaei et al., 2020). Zero rotation orientation only reaches the maximum thermal comfort when dimensions are 9x6x9 (best case scenario dimensions) and when the courtyard has wall type 2 (best case scenario wall type) ([2]Soflaei et al., 2020).

2.2.2.3: Wall Type

Wall type 2 achieves the highest thermal comfort when paired with a 1.5 x 1 x 1.5-dimension ratio and a 0 degrees rotation orientation ([2]Soflaei et al., 2020). Wall type 2 has the lowest U-value with 0.17, meaning the thermal comfort of the courtyard increased when the thermal lag of the wall was lower ([2]Soflaei et al., 2020). U-value is the transfer of heat through a structure. The better insulated a structure, the lower the U-value. Wall type 2 was not the best-case scenario for every simulation because with lower dimension ratios, such as when the height of the courtyard was modeled for 3 m, wall type 1 achieved the highest thermal comfortability ([2]Soflaei et al., 2020). However, design variables are dependent on each other and for the best-case scenario dimension ratios, wall type 2 was concluded to provide the best thermal comfortability ([2]Soflaei et al., 2020). Examples of wall type 2 include gypsum plasterboard, cement sand, and brickwork ([2]Soflaei et al., 2020).

2.3: Analysis of Courtyards in Hot-arid Climates

Previous research on courtyards in hot-arid climates have emphasized the importance of them in architecture as a passive cooling strategy ([1]Soflaei et al., 2017; [2]Soflaei et al., 2020; Mohammad, 2020; [3]Soflaei et al., 2016; Motealleh et al., 2018; Mohammadi et al., 2018; Zamani et al., 2018). These sources have shown that high aspect ratios, vegetation as a shading element, cross ventilation, and orientation greatly affect the thermal comfortability within courtyards, and that implementing additional climate responsive designs, such as low U-value wall types and high albedo surfaces (Nugroho et al., 2020) will even further lower relative air temperatures during the

summer months. Since the overall goal of a courtyard is to increase thermal comfort, courtyards in hot-arid climates will always seek to reduce solar radiation gain during the day, stabilize the relatively cooler nighttime temperatures through time/thermal lag, and maximize shading during the day.

Not every climatic responsive design was discussed in section 2.2.2, but natural ventilation and vegetation will be discussed here to show that the parameters were not forgotten but left out for a reason. The two aforementioned variables were fixed parameters in the study and thus were not a huge discussion part of ([2]Soflaei et al., 2020). Specifically, natural shading was not assigned for simulation modeling, meaning the temperatures of the model courtyard were based off of 100% sunlight hours ([2]Soflaei et al., 2020). This means that model courtyard temperatures could potentially be lower if shading elements were provided. Natural ventilation was active if indoor air temperatures are greater than 21.5 degrees C/ 70.7 degrees F and less than 27.5 degrees C/ 81.5 degrees F and natural ventilation through windows were operable at only 50% capacity ([2]Soflaei et al., 2020). Since ventilation was fixed, this study does not discuss how increasing or decreasing the parameters affects the overall thermal comfortability or energy use of the courtyard; it only shows that the fixed parameters of natural ventilation and vegetation have potential to achieve greater thermal comfortability. Thus, if it is assumed that the three fixed parameters could be changed to their best-case scenario, then energy usage would decrease even further because of passive cooling and heat mitigation strategies.

3: Cast Studies on Tropical Climates

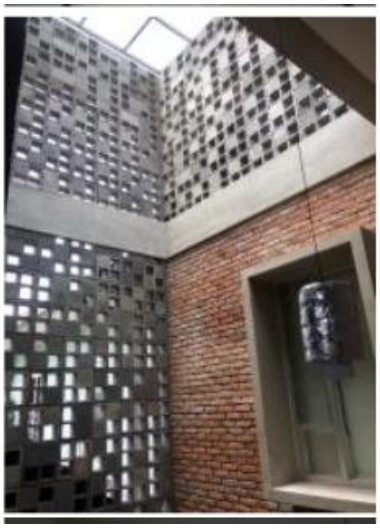
Tropical climates fall between the Tropic of Cancer and the Tropic of Capricorn (London, 2019), and include three microclimates: tropical rainforest, tropical monsoon, and tropical wet and dry (The British Geographer, n.d.). Examples of places of the microclimates include southeast Asia, parts of the Amazon forest, and the west coast of Africa (The British Geographer, n.d.). On an annual average, temperatures rarely move away from 80 degrees F (London, 2019), with yearly temperature fluctuation ranging from 21 degrees C/ 70 degrees F to 30 degrees C/ 85 degrees F (PHP, n.d.). In general, average precipitation ranges between 150 mm/ 5.9 inches to 270 mm/ 10.6 inches monthly (The British Geographer, n.d.), with relative humidity levels between 77% and 88% everyday (London, 2019).

This section will analyze two case studies of courtyard designs from Surabaya, Indonesia and Camagüey, Cuba in order to extrapolate climatic responsive solutions that use passive cooling to decrease energy usage and increase indoor thermal comfortability. Courtyards in these regions emphasize the influence of vegetation and dimension ratios for creating cooler day temperatures and passive night cooling (Nugroho et al., 2020; Rodríquez- Algeciras et al., 2018).

3.1: Surabaya, East Java, Indonesia

Nugroho et al. (2020) employs a field study to measure indoor air temperature reduction in six boarding houses in Surabaya, Indonesia. Out of the six boarding houses only houses 2, 3, and 6 have courtyards. So, for the purpose of this paper, the successful climatic responsive designs below will concentrate on the case studies of boarding houses 2, 3, and 6 that has courtyards.

Figure 3.1.a: Interior of boarding house #2



Credit: Nugroho et al. 2020

Figure 3.1.a: Inside of boarding house #2 with a perspective of a two-story high ventilated-black wall to an interior courtyard.

Figure 3.1.b: Interior of boarding house #6



Credit: Nugroho et al. 2020

Figure 3.1.b: Inside boarding house #6 showing a slim courtyard design.

3.1.1: Climate Classification of Surabaya, Indonesia: Hot-humid Climate

Indonesia has a tropical climate with hot, humid and rainy weather year-round and average relative humidity between 70-80% (Climates to Travel To, n.d.). Since Indonesia runs

through the equator, there are 12 hours a day year-round. With a hot and humid climate, the lower temperatures range from 22-25 degrees C/ 72-77 degrees F with highs ranging from 30-32 degrees C/ 86-90 degrees F (Climates to Travel To, n.d.). The southern side of Sumatra receives 4000 mm/ 155 inches of rain annually, with the months from October to December having an average rainfall of 400 mm/ 16 inches of rain (Climates to Travel To, n.d.).

Surabaya, located in East Java, Indonesia has a tropical climate with lower temperatures reaching 23.9 degrees C/ 75 degrees F and highs around 33.9 degrees C/ 93 degrees F (Weatherspark, n.d.) with an average temperature of 27.4 degrees C/ 81.3 degrees F (Climate Data Org, n.d.). Precipitation in the form of rain fall averages 1773 mm/ 69.8 inches annually with the wettest months receiving up to 287 mm/ 11 inches more of rain than the driest months (Climate Data Org, n.d.).

3.1.2: Successful Climatic Responsive Designs

3.1.2.1: Natural Ventilation

For the Nugroho et al. (2020) study, the boarding houses achieved passive cooling through continuous daily natural ventilation by employing ventilated-block brick walls that were open to cross breezes (Nugroho et al., 2020) The buildings with ventilated-block were cooler than buildings without it because the cross-breeze ventilation tempered humidity levels in the buildings, thus keeping indoor day temperatures at a lower relative temperature (Nugroho et al., 2020). Moreover, the buildings were 0.8-1.3 degrees C warmer during the night. This effectively means that the ventilated block decreased daytime air temperatures when it was hot and humid and slightly increased the nighttime temperatures to create a comfortable living environment throughout the entire day, thus having an overall higher thermal comfort (Nugroho et al., 2020). Boarding houses 2, 3, and 6 implemented both ventilated block and courtyards, which were proven to have lower relative temperatures than the boarding houses that did not have courtyards (Nugroho et al., 2020). Here, the conclusion that courtyards added to thermal comfort through exacerbating natural ventilation can be drawn.

Specifically, the indoor air temperature in boarding houses 2 and 6 were proven to be lower than the courtyard temperature during the daytime (Nugroho et al., 2020). Meaning that the

courtyard was able to ventilate and cool its surroundings, so the indoor air temperature of the building was lower than the outdoor air temperature of the courtyard. Within boarding houses 3 and 6, the vertical air exchange that occurred in the courtyard was able to decrease the indoor air temperature of the building, commenting on the importance of cross ventilation within a courtyard (Nugroho et al., 2020). Overall, the courtyard greatly added to the thermal stability and thus comfort of boarding house 2, 3, and 6, successfully acting as a passive cooling strategy.

3.1.2.2: Dimension Ratios

Since shading influences solar radiation within a courtyard, height to width ratios is an important climatic responsive design that can reduce indoor air temperatures (Nugroho et al., 2020). For example, the courtyards with boarding houses 2, 3, and 6 were three stories and were proven to have indoor air temperatures 4.9-7.3 degrees C/ 4.3 degrees F cooler than the boarding houses without courtyards during 12 pm (Nugroho et al., 2020), the hottest time of the day. Nugroho et al. (2020) discusses that buildings with narrow courtyards create better air exchange between indoor and outdoor temperatures because the building is affected by the cross ventilation when compared to a wider courtyard (Nugroho et al., 2020). Meaning that building ratios and courtyards ratios need to be considered in tandem during the architectural design process.

3.1.2.3: Orientation

The most influential orientation position for the courtyard is northeast-southwest because this direction provides shade for up to 65% of the courtyard area (Nugroho et al., 2020). Maximizing shade during the summer and minimizing it during the winter allows for higher thermal comfort year-round. In boarding houses 2 and 3, indoor air temperatures were 2% lower than outdoor temperatures, and both were orientated north-south (Nugroho et al., 2020). This shows that orientation has an effect on thermal comfortability.

3.2: Camagüey, Cuba

Old Havana, founded in 1519 by Spanish conquerors, had become one of the Caribbean's shipping centers by the 17th century (UNESCO, n.d.). To this day, the neoclassical and Baroque styles of the dense city incorporate courtyards into many homes (UNESCO, n.d.). Rodríquez-Algeciras et al. (2018) analyzes three courtyards in the city of Camagüey, Cuba that function as social and religious gathering spaces, and that are woven into the historical fabric of Camagüey. The courtyards are on average 30m x 30m which is larger than a courtyard that could be applied to a house, but they are considered vernacular architecture because of its historical ties and cultural contexts.

3.2.1: Climate Classification of Camagüey, Cuba: Tropical Savannah

The microclimate of Camagüey, Cuba is classified as a tropical savannah with an average temperature of 25.2 degrees C/ 77.36 degrees F, a mean relative humidity of 78%, an average annual rainfall of 1400 mm/ 55 inches (Rodríquez- Algeciras et al., 2018) and 7.33 hours of average annual sunlight hours per day (Holiday Weather, n.d.). The hottest months of June, July and August average 29 degrees C/ 84.2 degrees F, and the coldest months of December, January and February average 24 degrees C/ 75.2 degrees F (Rodríquez- Algeciras et al., 2018).

3.2.2: Successful Climatic Responsive Designs

3.2.2.1: Orientation

For rectangular courtyards, a N-S orientation proves to have lower mean radiant temperatures throughout the day when compared to rectangular courtyards-oriented E-W (Rodríquez- Algeciras et al., 2018). Dimension ratios, such as height to width, work in tandem with orientation. Mean radiant temperature in courtyards with a N-S orientation will be more highly influenced by a higher dimension ratio than the E-W orientation (Rodríquez- Algeciras et al., 2018). This means that the N-S orientation paired with a high aspect ratio will have a lower mean radiant temperature and higher thermal comfort than a high aspect ratio courtyard-oriented E-W (Rodríquez- Algeciras et al., 2018).

Although, here, it says that the N-S orientation has a lower mean radiant temperature, that does not discredit the cooling effects that the E-W orientation can produce. In this case, even though dimension ratios and orientation influence each other, overall, dimension ratios influence more heavily the mean radiant temperature of the courtyard (discussed more in 3.2.2.2). This is also shown for square courtyards with an E-W orientation and a high aspect ratio (Rodríquez-Algeciras et al., 2018).

3.2.2.2: Dimension Ratios

Dimension ratios in the Rodríquez- Algeciras et al. (2018) study is the most influential design for a courtyard because the ability to manipulate height and width allows for the reduction of mean radian temperature. This can be done by increasing shading and reducing direct solar radiation in the courtyard (Rodríquez- Algeciras et al., 2018). Ratios that have higher courtyard wall heights compared to its width have less direct solar radiation throughout the day during the summer (Rodríquez- Algeciras et al., 2018; Ghaffarianhoseini et al., 2015). So, in both the N-S and E-W oriented courtyards, the mean radiant temperature was lower than courtyards oriented in the NE-SW and NW-SE directions (Rodríquez- Algeciras et al., 2018).

Dimension ratios that are successful for decreasing solar radiation within courtyards will have height and width equal to 1.5 (Rodríquez- Algeciras et al., 2018; [2]Soflaei et al., 2020). Overall, square courtyards have lower mean radiant temperatures compared to rectangular courtyards (Rodríquez- Algeciras et al., 2018). Even though 1.5 is the optimal dimension, Rodríquez- Algeciras et al. (2018) suggests that any dimension ratio of height to width between 1 to 3 is recommended for warm-humid climates (Rodríquez- Algeciras et al., 2018). A 1.5 aspect ratio minimizes solar radiation throughout the year, thus increasing thermal comfort.

3.2.2.3: Vegetation

Rodríquez- Algeciras et al. (2018) didn’t use vegetation in its simulation modeling for its courtyard case studies but the study referenced a courtyard from Camagüey that did have vegetation and who studied the effects of vegetation in courtyards in temperate climates ([1]Taleghani et al., 2014). And it was concluded that vegetation is a natural cooling element that

can be implemented to achieve thermally comfortable temperatures, especially during the hottest times of the day which are from 10:00 h to 15:00 h (Rodríquez- Algeciras et al., 2018). Furthermore, it was concluded that courtyards without vegetation harbor a higher mean radiant temperature compared to those with vegetation (Rodríquez- Algeciras et al., 2018).

3.3: Analysis of Courtyards in Tropical Climates

Previous research on courtyards in tropical climates have emphasized the importance of them in architecture as a passive cooling strategy (Nugroho et al., 2020; Rodríquez- Algeciras et al., 2018; Ghaffarianhoseini et al., 2015; [2]Taleghani et al., 2012). These sources have shown that dimension ratios and cross ventilation play an important role in lowering relative temperatures and increasing thermal comfort. Dimension ratios that proved to have the highest thermal comfort are two to three stories tall and are narrower than they are wide. These aspects also have to be paired with openings to exterior air so that a cross ventilation can occur within the courtyard. This combination will effectively lower the temperatures within the buildings. Since the overall goal of a courtyard is to increase thermal comfort, courtyards in tropical climates will always seek to reduce solar radiation gain, to stabilize humidity levels, and to have plenty of natural ventilation throughout the entire day.

Not every climatic responsive design was discussed in section 3.1.2, but wall type and vegetation will be discussed here to show that the parameters were not forgotten but left out for a reason. Although Nugroho et al. (2020) references wall type and vegetation within the study, their parameters were not a pivotal part of the research. For example, Nugroho et al. (2020) says that the relationship between the indoor wall's temperature affects the temperature inside the room. This means that the walls that enclose the courtyard are essential to the microclimate condition of the courtyard and can be adjusted to create a higher thermal comfort (Nugroho et al., 2020). Specifically, the success of wall type hinges on its thermal inertia/time lag which stabilizes temperature fluctuations throughout the day (Nugroho et al., 2020). As for the impact of vegetation, courtyards will have lower relative temperatures during the day and higher relative humidity levels compared to a courtyard without vegetation (Nugroho et al., 2020). This is because vegetation blocks direct solar radiation from entering the courtyard, and because the vegetation and its soil collects moisture that can be released throughout the day, the overall climate of the

courtyard will be more thermally comfortable (Nugroho et al., 2020). Thus, if vegetation and wall type were implemented to any degree in a courtyard that previously didn't have either variable, the energy usage would further decrease as thermal comfortability increases.

In the Rodríquez- Algeciras et al. (2018) study, the climatic responsive designs of natural ventilation and wall type were not heavily studied so they were not included in 3.2.2, but they will be discussed here to show that the parameters were not forgotten but left out for a reason. Natural ventilation isn't abundant in the courtyards analyzed in the study and so the paper included references to prove that natural ventilation is needed to decrease daytime courtyard temperatures especially if vegetation is absent. Moreover, the impacts of natural ventilation can become diminished if the width of the courtyard is too wide (Rodríquez- Algeciras et al., 2018). Here, air exchange in the form of natural ventilation can have an overall negative effect on thermal comfort if dimension ratios are not carefully considered (Rodríquez- Algeciras et al., 2018). Yet, natural ventilation will provide more positive thermal conditions rather than negative ones, and thus should be implemented in courtyards in order to achieve higher thermal comfortability. Wall type according to thermal inertia/time lag wasn't mentioned, however increasing the albedo of the walls of the courtyard will help reflect some solar radiation thus increasing thermal comfort (Rodríquez-Algeciras et al., 2018).

4: Discussion and Conclusion

After analyzing hot-arid and tropical climates from around the world, many climatic responsive design solutions have been found to be applicable to the climate of Kapolei, Hawai`i. Natural ventilation, vegetation, wall type, dimension ratios, and orientation are the most influential design variables when it comes to the success rate of a courtyard, regardless of the climate. There is not much research on the tropical savannah climate of Hawai`i, so the cities of Yazd, Arizona, Surabaya and Camagüey were selected because their climates purposely and strategically overlapped to provide insight on climatic responsive designs for Kapolei, Hawai`i. Having similar successful designs will allow for the simulation, modeling, and application of them to the tropical savannah climate which is important because of the steady urban development that is occurring in Kapolei. With prolonged and sometimes intense urbanization in a place where space is finite and fossil fuels for cooling technologies are expensive, the courtyard can be a viable and successful vernacular architecture design strategy that can be implemented within the urbanization of Kapolei, O`ahu. Hawai`i is especially susceptible to climate change effects and thus climatic responsive design solutions will be chosen for the tropical savannah in hopes of spurring sustainable development.

Table 4.a: Climatic Responsive Parameters for Tropical Savannah Climate

Climatic Responsive Design	Examples	Influence
Natural Ventilation	Windows, wind catchers connected to courtyard and building	Cross ventilation keeps indoor air temperatures cool; increases air exchange
Vegetation	Trees, plants, shrubbery	Provides shade especially during midday; too much will increase humidity

Wall Type	Low to medium U-value	Better insulation will stabilize temperatures throughout the day and night
Dimension Ratios (height to width)	1.5:1 ratio or a 3:1 ratio; square shape	Minimizes direct solar radiation gain (until midday); increases air exchange
Orientation	North-south	Minimizes solar gain; maximizes shading

Table 4.a: Provides a concise description of the climatic responsive design parameters that can be used for a courtyard in the tropical savannah climate of Kapolei, Hawai`i.

Urban development is inefficient because it does not incorporate the components of regional climate, architecture, and inhabitants to be harmonious with each other. Urban development rapidly constructs homes, shopping centers, town houses, business plazas and the like without taking every environmental precaution possible. Here, environmental is referring to the physical environment of Kapolei as well as the sustainable, eco-conscience, and locally produced aspects of architecture. Table 4.a gives an overview of the most influential designs for the tropical savannah that can be taken into consideration to improve the environmental impacts that urbanization in Kapolei, Hawai`i creates. The procured climatic responsive designs in Table 4.a aim to create living spaces that are physiologically and psychologically comfortable for its inhabitants while also reducing the energy usage of each home or conglomerate of homes. Energy reduction can be achieved if urban development is constructed sustainably. Since the designs are highly tailored to the local environment, passive cooling and heat mitigation should be successful to the degree where the need for energy-intensive cooling technologies should be greatly minimized, if not irrelevant all together. In a time where climate change is being exacerbated by over consumption of fossil-fuels, courtyards offer a viable and successful solution to reducing energy consumption because of its emphasis on symbiosis between regional climate, inhabitants, and architecture.

4.1: Application of Courtyards in Kapolei, Hawai`i

Alongside the benefits of decreasing energy use and increasing indoor thermal comfortability, courtyards play a crucial role in traditions, culture, and social settings. The islands of Hawai`i are not traditionally tied to courtyards, however the culture of the Hawaiian people revolves around joint families, shared spaces, and camaraderie with nature- all of which are foundational of courtyard designs. Incorporating courtyards into urban development in the city of Kapolei will display the renaissance of and compliment Hawai`i's traditions and culture. With the expansion of Kapolei- and the greater west side of O`ahu- courtyards will play a significant role in decreasing energy use. Courtyards can be applied in many settings, whether that be in single family homes or a neighborhood.

Courtyards greatly imporve the microclimate of singular set up homes, and their presence also positively affects the climate of multi-story buildings and a conglomerate of buildings. For example, in Kapolei, a mass of homes is sectioned off into gentries which creates small-scale neighborhoods within the larger context of the city- a suburb if you will. This design can allow for future urban development plans to incorporate several courtyards per gentry where a dozen houses share a courtyard. Two simple versions of this may follow a rectangular design where a large outdoor courtyard is bordered by four houses each on the two long sides and two houses each of the short sides, or a circular design where a dozen homes border the courtyard as if they all share the same big backyard. To be sure, the courtyard is filled with grass, trees and shrubbery, a playground, and a pavilion. Combining these neighborhood elements with climatic design solutions will create a more comfortable and sustainable living situation. Specifically, the courtyard's climatic design solutions features will provide shade and air flow throughout the year decreasing home energy use and increase thermal comfortability, and the neighborhood elements will foster a sense of community. Future development of Kapolei is inevitable so incorporating courtyards as a sustainable design variant to vernacular architecture will be a successful and viable way to combat climate change.

The aim of this study was to perform a descriptive-analytic review of case studies of courtyards in order to provide climatic design solutions for the tropical savannah climate of Kapolei, Hawai`i. Accordingly, four courtyards were analyzed for successful climatic design

variables: natural ventilation, vegetation, orientation, wall type, and dimension ratios. Specifically, two courtyards in hot-arid climates within Iran and the US, and two courtyards in tropical climates within Indonesia and Cuba were analyzed to determine the appropriate climatic design parameters for the tropical savannah climate. Overall, the goal is to show that climatic responsive design solutions can increase thermal comfort and reduce energy usage within homes in Kapolei, Hawai`i. The main results are:

1. The height to width ratio of the courtyard and natural cross-ventilation are more influential in affecting air temperatures than the other climatic design features in a tropical savannah climate.

2. A design model that seeks to maximize thermal comfort and minimize energy usage was presented for the tropical climate based off the best-case scenarios and parameters from the four case studies.

3. Vegetation can provide important shading for the courtyard during the hottest times of the day, but too much can harbor air moisture and increase humidity levels.

4. A north-south orientation will provide the most shading for a courtyard.

In conclusion, this study shows that climatic responsive designs can become solutions to thermal comfort and energy reduction in the BSh climate of Kapolei, Hawai`i. Therefore, Table 1 parameters can be implemented for houses in this climate as a viable and successful vernacular architectural approach to increasing thermal comfortability and decreasing energy demand.

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