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# Analyzing present and future climatic trends on the thermal energy performance of attic structures

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**Analyzing present and future climatic trends on the thermal energy performance of attic structures**

by

**Kahntinetta M. Pr'Out**

A thesis submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of  
**MASTER OF SCIENCE**

Major: Mechanical Engineering

Program of Study Committee:  
Baskar Ganapathysubramanian, Major Professor  
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Ames, Iowa

2016

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## DEDICATION

I would like to dedicate this thesis to Marc, Angie, Marc Jr., and Maurice. They say you can't choose the family you're born into, but even if I could, I wouldn't have chosen any other bunch. Their unconditional love and support has helped me reach heights I never dreamt possible. This accomplishment is as much theirs as it is mine.

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**ABSTRACT**

Climatic changes have resulted in negative impacts across the globe. Few industries are immune to these impacts, the buildings energy sector being no exception. While the entire envelope contributes to the energy demands of a typical building, the attic space proves to be unique. These unique spaces experience complex heat and mass transfer phenomena due to its contents, structure, as well as construction materials and the associated properties. Significant heat loss or gain occurs at the interface of the attic floor and ceiling of an occupied space; therefore, it has become imperative to understand the energy characteristics of attic spaces. Even more so now since climatic changes are causing higher outside temperatures.

This work examines the impacts of climate trends on the energy performance of attic spaces over the next thirty years. Considering six unique attic geometries, configured to architectural standards, analyses are performed against four climatic scenarios within six major United States cities. Investigating three thermal characteristics: attic air temperatures, peak roof deck temperatures, and thermal loads this work is able to explore the design robustness of each geometric configuration across several climate zones. While this work can be conducted and/or validated through experimental work and field tests, it was done using a novel numerical framework. Results from this work show that with a general increase among attic surface temperatures and surface fluxes which results in higher attic air temperatures, peak roof deck temperatures, and larger thermal loads, specifically cooling loads. Additionally, despite differences in attic geometries, similar light weight construction shows that the average peak times were similar for all structures located within the same geographical location.

## CHAPTER 1

### GENERAL INTRODUCTION

#### 1.1 Thesis Organization

This master's thesis is composed of a future journal publication entitled, *Exploring future climate trends on the energy performance of attics: Part 1 - Standard roofs*. This is the first installment of a two part project done in conjunction with personnel at the Fraunhofer Center for Sustainable Energy Systems in Boston, MA. This work examines the influence of climatic changes on the thermal characteristics and thus energy performance of six unique attic configurations for the next thirty years. This first installment focuses on attic spaces configured with standard roof deck materials. Before this article is presented, there is a general introduction of the motivating factors behind this research and a synopsis of previous works in the field. The modified publication is presented in its entirety: abstract, introduction, methods, results, discussions, conclusions, and references. Finally, this thesis concludes with a concise outline for avenues of potential work.

#### 1.2 Introduction: Thermal Energy Performance of Attic Spaces

Climate changes are continually impacting a variety of interests and industries (Patton, 2013). Energy sectors are arguably amongst the most impacted industries as rising average temperatures, varying precipitation levels, changing seasonal patterns and the intensity of extreme weather patterns all impact energy demands (Patton, 2013; Wilbanks, Bilello, Schmalzer, & Scott, 2012). Of the four energy sectors, the buildings sector has the greatest potential to alleviate and adapt to these climatic changes (Crawley, Hand, & Lawrie, 1999;



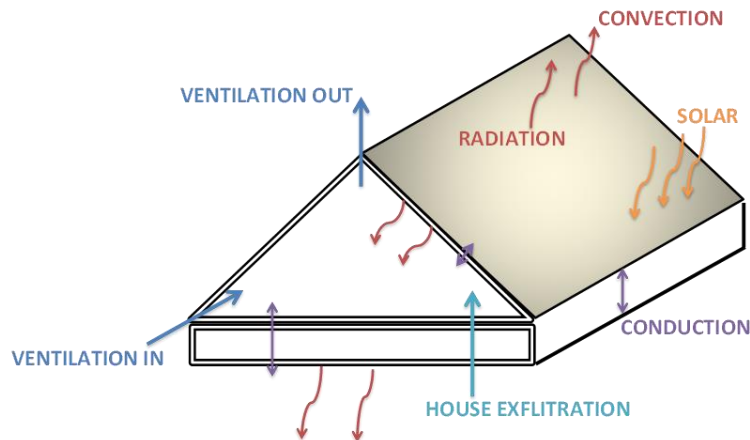
IPCC, 2001; Patton, 2013). Additionally, the building sector perhaps has the most responsibility to address these impacts as green-house-gas emissions from the buildings sector exceeds both the industrial and transportation sectors (Miller et al., 2013). While climate change is dynamic and varies by regional location, the general trend of increasing average temperatures results in an increase in cooling loads and a simultaneous decrease in heating loads (Kalvelage, Passe, Rabideau, & Takle, 2014; Romero-Lankao et al., 2014; Wilbanks et al., 2012). Adaptations within the construction standards and the utilization of energy efficient technologies could potentially alleviate these impacts. Existing standards such as American Nation Standards Institute/American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ANSI/ASHRAE) 90.1, ANSI/ASHRAE 90.2, and the International Energy conservation Code (IECC) would be affected as a result of climatic changes (ASHRAE, 2007, 2010; IECC, 2012). While previous work has exclusively focused on the energy performance of light commercial properties, recent work has begun to include residential properties as they also contribute to energy consumption within the United States (Jentsch, James, Bourikas, & Bahaj, 2013; Kalvelage et al., 2014; Patton, 2013; Wang, Chen, & Lafayette, 2014).

The United States Department of Energy (DOE) has classified energy consumption into four distinct sectors: transportation, residential, commercial and industrial (U.S. Department of Energy, 2012). The residential and commercial sectors, known as the buildings sector, consumed 39 quads of energy or 41% of the total energy consumption within the United States (U.S. Department of Energy, 2012). Where 1 quad is equivalent to  $10^{15}$  British thermal units (BTU) or  $1.005 \times 10^{18}$  joules (J). The energy demands of an average building, in terms of conditioning the occupied space is determined by the thermal characteristics of its envelope (Bianchi, Miller, Desjarlais, & Petrie, 2007). In a typical residential building, 47% of the energy is being used to

heat and cool the occupied space (U.S. Department of Energy, 2012). While the entire envelope contributes to the energy demands of a building, attic spaces prove to be unique. Since the roof and attic space are subjected to greater temperature extremes than comparison to the remainder of the building envelope, these spaces experience a number of phenomena and contribute significantly to the building load (Miller et al., 2013). Attic spaces are responsible for 12% of the heating requirements and 14% of the cooling requirements. This equates to attics consuming approximately 1.5 quads of energy for heating and 1.8 quads of energy for cooling (U.S. Department of Energy, 2012). With a significant amount of heat transfer occurring at the interface of the attic floor and ceiling, it is imperative to examine the energy performance of attic spaces as climatic changes occur.

Attic structures vary in their structural design, construction materials and even functional purpose. Engineers, architects, contractors and even homeowners can tailor specifications to not only meet construction and zoning standards but aesthetic appeal as well (Fontanini, Kosny, Shukla, & Ganapathysubramanian, 2016). Well-designed attic spaces can either mitigate or amplify the thermal energy that passes through the system, particularly the area between the attic floor and ceiling of the occupied space (Fontanini et al., 2016). The study of attic energy performance and thermal characteristics however, comes with a unique set of challenges (Fallahi et al., 2013; Fontanini et al., 2016). Unlike the remainder of the building envelope, the attic space experiences high thermal and radiate loads, large ventilation rates, significant temperature swings and moisture accumulation (Fontanini et al., 2016). Additionally, Heating Ventilation and Air Condition (HVAC) systems and air ducts are often located within an attic space (Fontanini et al., 2016). As illustrated in figure 1, all modes of heat transfer (conduction, convection, and radiation) as well as mass transfer (exfiltration and ventilation) can occur within the confines of

an attic space at any given time. Due to these unique characteristics, energy estimation of attic spaces and its contribution to the energy demands of building systems has proven to be an interesting topic worth researching for well over fifty years.



**Figure 1:** Schematic of the heat and mass transfer phenomena occurring within a gable-ended attic space.

### 1.3 Literature Review

There are numerous laboratory experiments, field tests, and numerical methods that contribute to the research and development of attic thermal and energy performance. As this area has many research avenues, this literature review will focus on the research pioneers and key numerical research developments in attic thermal performance.

The evolution of attic energy performance research up to the mid 1990's has been thoroughly detailed in the ASHRAE report RP717 (Ober & Wilkes, 1997). In an attempt to summarize the works pertinent to this research, we focus on the pioneers of the field and key developments in numerical methods. Pioneering the research of attic energy performance was the experimental work of F.A. Joy (Ober & Wilkes, 1997). Using two three-dimensional configurations, the gable-ended and flat roofs, heat flow into the occupied space was measured

with and without radiant barriers. By analyzing heat transfer with and without radiant barriers for two geometric configurations, several useful conclusions were made for both the heating and cooling seasons (Ober & Wilkes, 1997). As a result of many different laboratory experiments and field tests such as Joy's, numerical tools have since been developed. The first numerical tool to model and estimate the thermal performance of attic spaces was developed and used by B.A. Peavy (Ober & Wilkes, 1997; Peavy, 1978; "Summer Attic and Whole-House Ventilation," 1979). Peavy's model followed the mathematical analysis presented by Joy, and included an hourly calculation of temperatures and heat flows within the attic space (Ober & Wilkes, 1997; Peavy, 1978; "Summer Attic and Whole-House Ventilation," 1979). Showing very good agreement with the field test measurements of an experimental work done by D. M. Burch and his predicted values, Peavy's model proved to adequately predict the thermal performance of attic spaces in various geographical locations and operating conditions (Ober & Wilkes, 1997; Peavy, 1978). This initial computer program was fundamental in creating a new research branch within the area of attic energy performance.

The accuracy of numerical tools for modeling the thermal performance of attic spaces did not eliminate the need for experimental research but rather opened a new avenue for roof and attic research. Numerical methods were developed alongside laboratory experiments and field tests as new materials, constructions, and operating conditions were investigated. More often than not, experimental works serve as bench-marking and verification processes for the development computer programs within numerical research. Expanding on the work of Peavy and serving as the cornerstone for the standard calculation procedures of estimating thermal performance within attic spaces, were the works of D. G. Ober and K. E. Wilkes (Ober & Wilkes, 1997). To date, this work has been collected into an ASTM C1340 standard and is

widely accepted by similar societies as the consensus method for estimating heat fluxes between the attic floor and occupied space ceiling (ASTM C1340, 2011; Ober & Wilkes, 1997). The ASTM C1340 standard, since its inception, has often been updated to include experimental and numerical works proven to influence attic energy performance (Fallahi et al., 2013; Fontanini et al., 2016). For example, solar radiation algorithms, latent heat effects, air stratification effects, and the influence of air ducts and trusses have all proven to influence the evolution of thermal energy within attic spaces and thus its energy performance (Fallahi et al., 2013; Fontanini et al., 2016). However, despite the inclusion of new research advances, the numerical framework has yet to be updated (Fontanini et al., 2016). Current research in numerical methods has since been developed across multiple national laboratories, universities, and industries to address this issue. This work will focus on the Fraunhofer Thermal Model (FATM) a recent development as it is the tool that has been utilized to aggregate the data.

Thoroughly detailed in the cited works (Fontanini et al., 2016), FATM is a novel computer program developed from the identified limitations of the ASTM C1340 standard. This framework allows for multiple benefits over the current standard, including: updated programming language, modular class structure, and improved numerical algorithms. This updated architecture allows for usability, flexibility, and scalability of the entire framework. Although self-sustaining, FATM is also compatible with whole-building simulation software. In addition to the framework update, the FATM program also allows for input variations in areas not previously considered by other programs. Prior numerical tools are only capable of inputting convex roof and attic configurations limiting the sample size to four specific structures: gable-ended, flat, saltbox, and shed. FATM can take both convex and non-convex structures, greatly expanding the sample size. Prior numerical methods did not consider varying occupied space

temperatures, or temperature dependent properties of attic construction materials. This novel framework is able to input occupied space temperatures based on various set back schedules during weekdays, weekends, and holidays as well as consider temperature dependent properties of attic envelope construction materials. Benchmarking efforts were conducted and discussed within the cited works. There was a relative  $L_2$  error of 8% found after conducting an intermodal comparison between FATM and the ASTM C1340 standard (ASTM C1340, 2011; Fontanini et al., 2016). According to the author, this is attributed to heat flux measurements on the outside of a roof deck construction of a gable-ended attic configuration (Fontanini, Kosny, Fallahi, Shukla, & Ganapathysubramanian, 2015; Fontanini et al., 2016) These unique capabilities, offered solely by the FATM framework, along with the fact that there is a desire to update the existing standard amongst notable societies are the reasons for which we utilize this computer program.

#### **1.4 Objectives: Contributions of this work to the energy and buildings industry**

This work can contribute to the buildings energy sector and related fields in a number of ways. First and foremost, it expands upon the existing knowledge base of attic thermal and energy performance. The utilization of future climatic data along with the numerical framework addresses areas not previously included in prior laboratory experiments, field tests, and/or numerical methods. This work accounts for climatic changes and its influence on attic thermal performance while expanding the attic configurations which can be analyzed. This work will also begin to incorporate energy saving technologies and investigate its influence on attic energy performance as climatic changes occur. By including these areas into our work, we are able to draw conclusions about the design robustness of six unique attic/roof configurations in six United States locations. In addition to contributing new knowledge to the field, this work also

illustrates the need for an update of current numerical methods used to estimate heat fluxes through. An update in the numerical framework of the existing standard would allow for research on a broader amount of attic structures under ever-changing environments and operating conditions. We believe that a number of populations can benefit from this work, including: engineers, architects, contractors, and even homeowners.

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## CHAPTER 2

### EXPLORING FUTURE CLIMATE TRENDS ON THE THERMAL PERFORMANCE OF ATTICS: PART 1 – STANDARD ROOFS

Modified from a paper submitted for publication to *Energy and Buildings*

Kahntinetta M. Pr'Out<sup>1</sup>, Anthony D. Fontanini<sup>2</sup>, Jan Kosny<sup>3</sup>, Baskar Ganapathysubramanian<sup>4</sup>

#### 2.1 Abstract

Attic spaces experience complex heat and mass transfer in comparison to the rest of the building envelope. The thermal energy evolution of these unique spaces is further complicated due to complex geometries, multi layered material components, their non-linear material properties, and geographical locations. The proper design of attics plays a significant role in the amount of thermal energy transferred across the ceiling to the occupied space and the energy usage of the building envelope. This is especially important in the context of changing climatic conditions which affects the energy demand of residential as well as commercial buildings.

This study investigates the impact of current and predicted future climates on different attic forms in multiple locations across the U.S. For this analysis we utilize a recently developed, validated attic energy analysis model, the Fraunhofer attic thermal model. Six attic geometries (constructed according to architectural standards) are considered. These geometries are analyzed under four climatic scenarios in six major U.S. cities. We investigate several energy characteristics of roofs including thermal loads, peak roof deck temperatures, and attic air

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temperatures. The identification of energy usage and robustness to climatic changes can contribute to improved attic construction design standards. We envision this work informing architects and engineers in designing robust attic spaces that create more sustainable buildings for the future.

## 2.2 Introduction

The impacts of changing climatic conditions can be felt all over the world. Some of these impacts in North America include; increase occurrence of severe heat events, reduction in frost days and low snow years, and increases in precipitation variability and drought severity (He, Yang, & Srebric, 2005), (Peng & Wu, 2008), (Romero-Lankao et al., 2014). While these climate changes critically affects the energy sector, it appears that buildings have the highest mitigation potential to these changes (Crawley et al., 1999; IPCC, 2001). Although these climate changes vary from region to region, in the next few decades cooling loads are generally expected to increase while heating loads are generally expected to decrease (Kalvelage et al., 2014; Romero-Lankao et al., 2014; Wilbanks et al., 2012). Currently, the building sector consumes a total of 39 quads and of this total, residential buildings used 54% while commercial buildings used 46% (U.S. Department of Energy, 2012). Space heating and cooling energy demands from the building envelope represent about 47% of the energy demands within a typical residential/commercial property (U.S. Department of Energy, 2012). Attic spaces alone are responsible for 12% and 14% of the space heating and cooling requirements, respectively (U.S. Department of Energy, 2012). *Thus, attics are responsible for using 1.5 quads for heating and 1.8 quads for cooling.* Modifications to construction standards, the use of new energy saving technologies (phase change materials, radiant barriers), and robust designs are potential solution strategies to help mitigate increases in space heating/cooling demands. It is, thus, important to

examine the performance of different attic designs as a function of climate change in order to determine how construction standards and other strategies can be leveraged. This will in turn inform standards like ANSI/ASHRAE 90.1(American Society of Heating, 2013), ANSI/ASHRAE 90.2 (American Society of Heating, 2013), and IECC (IECC, 2009), that determine building envelope, Heating Ventilation and Air Conditioning (HVAC) sizing, and ice/snow melt systems.

The attic (which is the area between the attic floor and ceiling of the occupied space) is responsible for significant heat loss or gain from the building envelope. Thermal energy is transferred through the attic components (roof decks, gables, eaves, and attic floor) by means of conduction, convection, radiation along with mass transfer, by means of ventilation, exfiltration, and duct air leakage (see Figure 1). Proper construction of attic spaces promotes minimal heat loss or gain during the heating and cooling seasons. This heat and mass transfer differs drastically from the remainder of building envelope because of the unique characteristics of attic space (Fontanini et al., 2016). For example, attic spaces can contain HVAC systems and air ducts, in residential buildings they can function as storage with large amounts of thermal mass. Additionally, these spaces experience substantial thermal loads, large ventilation rates, and drastic temperature swings (Fontanini et al., 2016) as they are usually unoccupied space. Due to these unique characteristics, energy estimation of attic spaces has proven to be difficult (Fallahi et al., 2013; Fontanini et al., 2016).

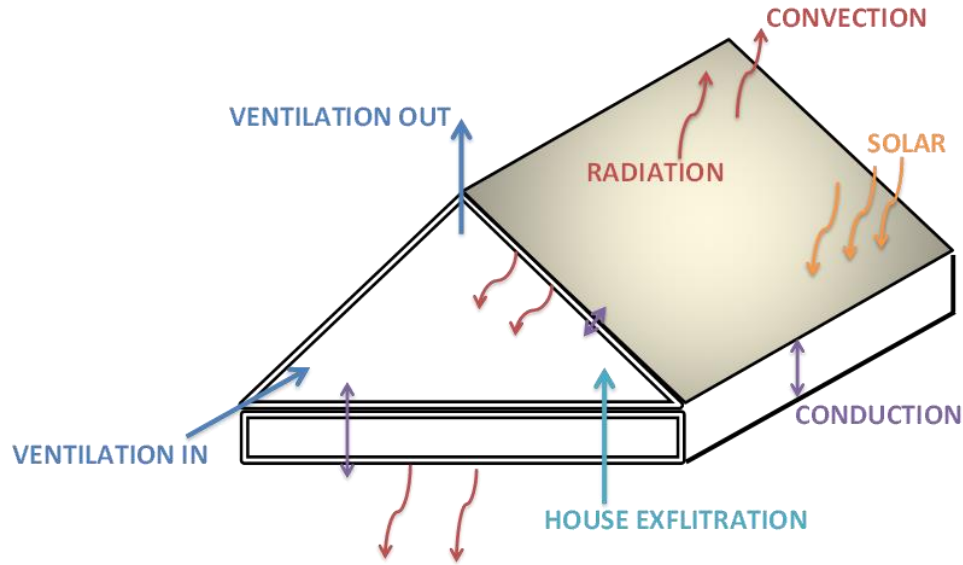


Figure 1: Illustration depicting the complex heat and mass transfer phenomena occurring within a gable-ended attic space.

F. A. Joy pioneered the development of attic energy performance analysis by studying heat flow within two geometric configurations (flat and gable-ended roofs) (Ober & Wilkes, 1997). Heat flow into the conditioned space was measured, with and without the presence of radiant barriers under laboratory controlled steady state conditions. Joy provided data for both the heating and cooling seasons. Several useful conclusions were drawn including comparisons between the gable-ended and flat structures, as well as observations concerning ventilation schemes. Since this foundational work, many laboratory experiments, field tests, and numerical investigations have been dedicated to unraveling the complexities and performance of attic spaces (Ober & Wilkes, 1997). An exhaustive discussion of this research until the mid-1990's is outlined in ASHARE report RP717 (Ober & Wilkes, 1997). To briefly summarize, the use of computer programs to model the thermal performance of attic spaces was first developed by B. A. Peavy (Ober & Wilkes, 1997; Peavy, 1978). B. A. Peavy validated results with experimental data collected from D. M. Burch (Ober & Wilkes, 1997), a field study following Joy's initial

work. Peavy also utilized Joy's mathematical analysis as algorithms (ASHRAE, 2007; Ober & Wilkes, 1997; "Summer Attic and Whole-House Ventilation," 1979; Wilkes & Rucker, 1983). Additionally, work done by D. G. Ober and K. E. Wilkes was fundamental in creating the standard calculation procedure for accurately approximating the heat flux through the ceiling of residential/light commercial buildings (ASTM C1340, 2011; Ober & Wilkes, 1997; Wilkes & Rucker, 1983). This work was collected into an ASTM standard C1340 developed by K. E. Wilkes (ASTM C1340, 2011). C1340 has been widely accepted as a consensus method by ASHRAE (ASTM C1340, 2011) and ASTM (ASTM C1340, 2011). Further research has since been incorporated into the existing standard. Some of this research included improvements to the solar radiation algorithms (Wilkes, n.d.), latent heat effects ("CU-7472.pdf," n.d.), air stratification (Medina, O'Neal, & Turner, 1998), and the influence of air ducts and trusses (Ober & Wilkes, 1997).

Current rapid advances in construction materials and complex roofs, as well as limitations in ASTM C1340 (ASTM C1340, 2011) have resulted in the development of an updated model called the Fraunhofer attic thermal model (FATM) (ASTM C1340, 2011; Fontanini et al., 2016). We refer the interested reader to (Fontanini et al., 2016), which details the development and validation of FATM. This framework builds upon C1340 and is seen as the state-of-art in attic energy simulation software primarily due to the following advantages: updated programming language that utilizes modern software engineering principles, modular class structure that enables easy extensibility and usability, and improved numerical methods for efficient solution of the nonlinear system of equations. The FATM framework is a stand-alone software framework in its ability to perform calculations without the need of additional programs. However careful software design considerations allow integration of FATM with total

building simulation tools. Additionally, the framework also allows for varying inputs such as geometric configurations, construction materials and associated temperature dependent material properties, as well as varying conditioned space temperatures. This is in contrast to predecessor attic thermal models that are only able to input constant conditioned space temperatures, and do not consider temperature dependent properties of attic construction materials. Additionally, only convex geometries are allowed within the ASTM C1340 standard, limiting the sample size to four attics structures (gable-ended, saltbox, flat, and shed roof attics). In contrast, FATM is able to input both convex and nonconvex geometries, expanding the range of attic structures that can be analyzed. Finally, as novel construction materials (with complex, temperature dependent thermal responses) are developed, this framework is able to seamlessly account for these complex thermal behaviors to predict attic energy performance. In addition to the standard quantity of interest -- heat flux on the outside of the attic floor (i.e. ceiling of occupied space) -- FATM is capable of computing other quantities of interest including: attic air temperature, as well as surface temperatures and surface fluxes on either side of each bounding surface of the attic space<sup>5</sup>. We leverage the capabilities offered by FATM to calculate several energy performance indicators of attic spaces that form the basis of this study.

This study quantifies the effects of future climate trends on the thermal characteristics of various attic spaces in terms of thermal loads, peak roof deck temperatures, and attic air temperatures. Six unique roof structures were configured based on architectural and construction standards (ASTM C1340, 2011; Ramsey, Sleeper, & Bassler, 2008). Construction files were also created based on the standard construction materials used within attic spaces according to the Department of Energy (DOE) and architectural codes (ASTM C1340, 2011; Ramsey et al., 2008; U.S. Department of Energy, 2012). Current and future climate trends were established for six

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<sup>5</sup> Extensive benchmarking and accuracy efforts have been conducted in (Fontanini et al., 2016).



major cities within the continental United States (Patton, 2013). Given these geometric configurations, material components, and current and future climate trends we analyzed a total of 144 data sets to explore the robustness of each roof structures across all geographical locations as climatic changes evolve over the next thirty years.

The contents of this paper are as follows: A detailed description of the geometric configurations, materials and components, as well as the climate data inputs is discussed. The governing equations and the associated simulation procedure of FATM are explained. The calculations of the quantities of particular interest are outlined. Graphical illustrations of the results obtained via FATM and an in-depth discussion of the research findings is covered in the results and discussion section. Finally, this work concludes with potential avenues of future research.

## **2.3 Methods**

This section discusses the various inputs that drive the FATM framework, the governing equations for FATM, the simulation procedure, and solution verification, along with the quantities of interest.

### Description of Inputs

The inputs that FATM requires for calculating energy usage metrics are as follows: (a) geometric representation of the attic, (b) material properties used in construction of the attic, (c) construction components (for the roof decks, gables, and attic floors), and (d) weather data. We discuss each of these aspects in detail.

#### *Attic configurations*

We consider six unique attic geometries that are commonly used in continental US: gable-ended, gable-ended with a dormer (simply referred to as dormer), flat, hip, combination

and mansard. These are schematically illustrated in Figure 2. The gable-ended and flat geometric configurations are standard constructions found in residential and light commercial properties (ASTM C1340, 2011; Ober & Wilkes, 1997). The remaining geometries are common attic shapes and architectural features often found in residential buildings in different regions of the U.S. It is worth noting that without the capabilities of FATM, the convex hip roof and mansard roof, along with the nonconvex gable with dormer roof and combination roof cannot be accurately simulated. Each of the six structures has an attic floor dimension of 8.54 m x 16.76 m, which is the attic floor geometry used in the ASTM C1340 standard (ASTM C1340, 2011). All of the configurations are oriented with the shorter side of the building facing north<sup>6</sup>. The pitch of the roof varies slightly for each geometric configuration based on the architectural standards used in this analysis (ASTM C1340, 2011; Ramsey et al., 2008). The flat roof has the lowest pitch of 0:12 (Ramsey et al., 2008). The gable-ended, dormer, and hip roofs have similar medium pitches of approximately 5:12 (ASTM C1340, 2011) on the major axes with the hip roof also having a pitch of 3:12 on the minor axis (Ramsey et al., 2008). The mansard and combination roofs have the highest pitches of the attics considered. The mansard roof has pitches on the top structure similar to the hip roof but, for the lower portion has a pitch of 24:12 (Ramsey et al., 2008). The top portion of the combination roof has a pitch of 12:12 on the top major axis and a pitch of 11:12 on the minor axis; while the lower portion has a pitch of 4:12 (Ramsey et al., 2008). Soffit/ridge venting configurations are considered for venting strategies for these attics with the exception of the flat roof which used only soffit vents. The venting areas are held consistent for each configuration with a soffit vent area of 0.64 m<sup>2</sup> and a ridge vent area of 0.32 m<sup>2</sup>, similar to the ASTM C1340 standard (ASTM C1340, 2011). Since it is recommended that air

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<sup>6</sup> Although the heating and cooling loads vary slightly as the orientation of the building changes, it was seen that the relative changes due to changing orientation are not significant.

ducts be placed in the conditioned spaces to reduce energy losses (IECC, 2009; IRC, 2009), these attic spaces do not have air ducts running through the enclosed space. We emphasize that these configurations (construction materials and shape) were chosen according to existing architectural and zoning standards (ASTM C1340, 2011; Ramsey et al., 2008), which ensure practical relevance of this work.

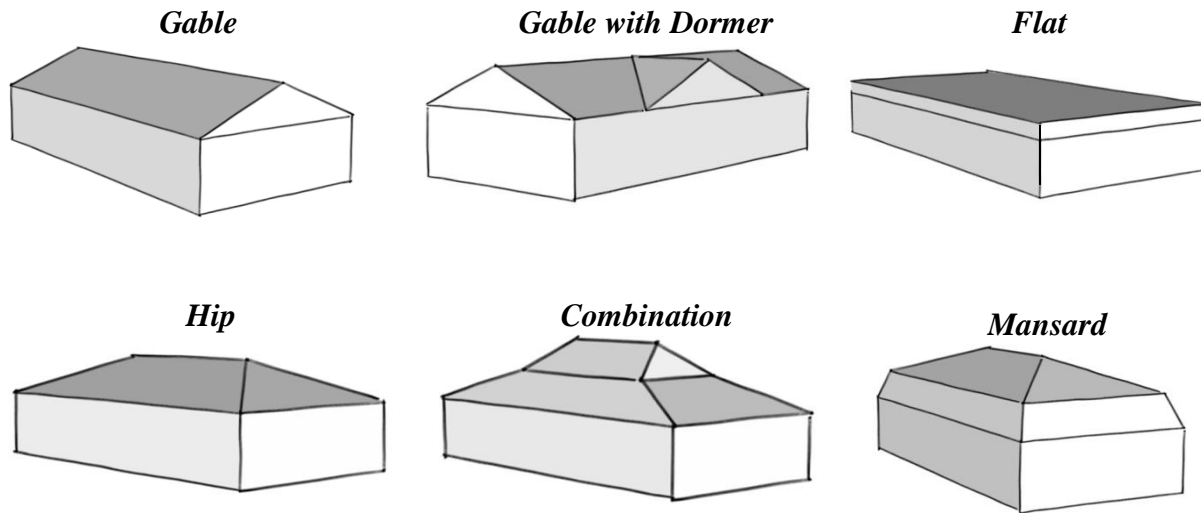


Figure 2: Illustrations of the attic geometries used in this work. Visualized using View3D (Walton, 2009) and SketchUp (“SketchUp Instructions,” 2010).

#### *Materials and Component configurations*

Each of the six geometric configurations is composed of the same set of construction material. Standard construction materials and the associated properties are from the ASTM C1340 standard report, and shown in Table 1 (ASTM C1340, 2011). Each component (roof deck, gable, and floor) of the attic structure is composed of two or more material layers according to ASTM C1340 (ASTM C1340, 2011), Table 2. We keep the material properties and construction identical for each geometry allowing for consistent comparisons between attic structures.

Table 1: Table of materials and the corresponding properties.

Material	Thickness [m]	Thermal Conductivity [W/m*K]	Density [kg/m <sup>3</sup> ]	Specific Heat [J/kg-K]
<b>Gypsum board</b>	0.013	0.160	801	1089
<b>R-30 insulation</b>	0.241	0.047	9.611	795
<b>Shingles</b>	0.006	0.082	1121	1256
<b>Felt</b>	0.002	0.082	1121	1507
<b>Plywood</b>	0.013	0.115	545	1214
<b>Rafters</b>	0.089	0.118	449	1633
<b>Hardboard siding</b>	0.011	0.215	1121	1172
<b>Studs</b>	0.038	0.118	1632	1633

Table 2: Table of components and the corresponding layers listed outside to inside relative to the attic air.

Component	Number of Layers	Material Layers
<b>Roof deck</b>	3	Shingles, felt, and plywood
<b>Gable</b>	2	Hardboard siding, studs
<b>Attic floor/ceiling</b>	2	Gypsum board, R-30 insulation

*Climate data: TMY3 and FTMV*

In addition to six unique geometric configurations, this work considered six geographic locations within the United States along with their respective heating and cooling seasons (Cedar Lake Ventures, n.d.). The cities include: Atlanta, Georgia; Baltimore, Maryland; Los Angeles, California; Minneapolis, Minnesota; Phoenix, Arizona; and Seattle, Washington. Each city is categorized by ASHRAE 90.1 (American Society of Heating, 2013), into a climate zone based on temperature and a subzone based on precipitation levels. Each city has a unique period for both the heating and cooling seasons<sup>7</sup>. Current climate data, known as typical meteorological year 3 (TMY3), can be found on the National Solar Radiation Database (“National Solar Radiation Data Base,” 2015). The TMY3 files are composed of hourly meteorological values derived from measurements collected between 1991-2005 (“National Solar Radiation Data

<sup>7</sup> The heating and cooling seasons were gathered from WeatherSpark (Cedar Lake Ventures, n.d.). The heating season corresponds to the “cold” season, and the cooling season corresponds to the “warm” season.

Base,” 2015; Patton, 2013). This data represents a “typical” meteorological year for 1,020 various locations. We utilize future typical meteorological year (FTMY) climate data sets reported by S.L. Patton and E. S. Takle (Patton, 2013). Developed by coupling model-projected climate changes with existing TMY3 files, these unique future weather data sets better describe the microclimate occurring within a finite radius of the six geographic locations as regional climate changes occur. This is essentially done by taking into account the unpredictability of climate change as a result of greenhouse gasses (Crawley et al., 1999; IPCC, 2001; Kalvelage et al., 2014; Patton, 2013). This combined dynamical downscaling and typical meteorological year data provided higher resolution results across specific locations (Patton, 2013). Similar to TMY3 weather data, the FTMY weather data projected climatic impacts over the next 30 years. The FTMY data sets primarily take into account varying levels of carbon dioxide within the atmosphere; therefore the future climatic data sets are labeled by CO<sub>2</sub> levels (low, moderate, and high). It is important to note that classification differs for each city, i.e. what is considered low CO<sub>2</sub> for Los Angeles may not be the same as low CO<sub>2</sub> levels in Atlanta. The novelty of using current and future climate trends sets this research apart in its ability to identify trends of attic energy performance as climatic conditions change. With these 6 geographical locations, 6 attic configurations, and 4 climatic scenarios, we analyzed a total of 144 unique data sets.

*Table 3: Definition of the cities using in the simulations and their respective heating and cooling seasons.*

City	State	Climate Zone	Heating Season	Cooling Season
Atlanta	GA	3A	November 30 – February 21	May 23 – September 19
Baltimore	MD	4A	December 2 – March 2	May 30 – September 16
Los Angeles	CA	3B	November 29 – March 17	July 2 – September 25
Minneapolis	MN	6A	November 26 – March 6	May 21 – September 16
Phoenix	AZ	2B	November 20 – March 1	May 30 – September 21
Seattle	WA	4C	November 13 – March 2	June 22 – September 12

### Governing equations

The governing equations that FATM is based on are formulated by performing energy balances on each control volume of the attic. The attic surfaces and the enclosed attic air space are treated as one dimensional independent control volumes in which all three modes of heat transfer in addition to mass transfer are included in the governing equations (Fontanini et al., 2016; “Summer Attic and Whole-House Ventilation,” 1979). Thus, if given a gable-ended roof with  $n_s$  surfaces, a total of  $N = 2n_s + 1$  equations are solved for this geometric configuration since two equations are needed for each bounding surface and one equation is needed for the enclosed attic air space. The governing equations are divided into three different energy balance equations (as given in ASTM C1340 (ASTM C1340, 2011) and FATM (Fontanini et al., 2016)): one for the physics occurring on the outer surfaces of the attic space, one for the physics occurring in the area facing the inner surfaces of attic space, and a one for the attic air control volume (Fontanini et al., 2016; “Summer Attic and Whole-House Ventilation,” 1979). The physics accounted for on the outside surfaces of an attic space are heat fluxes associated with conduction, radiation, and convection (Ober & Wilkes, 1997), Eq. 1. Also included in the governing equation for the outer surfaces is the solar radiation incident occurring on the outside of a give surface with respect to its solar absorptivity and radiation exchange with the surroundings.

$$q_o(i) + q_{ro}(i) + q_{co}(i) + \alpha(i)q_s(i) = 0, \text{ for } i = 1,2,3 \dots n_s \quad (1)$$

The energy balance on the inside surfaces of the attic space accounts for the heat fluxes associated with conduction, convection, radiation exchange between the inside surfaces of the attic, radiation exchange between ducts and trusses, and effects of absorption or desorption of moisture (Ober & Wilkes, 1997), Eq. 2.

$$q_i(i) + \sum_{j=1}^{n_s} q_{rj}(i) + q_{ci}(i) + q_{moist}(i) + \frac{Q_{rD}(i)}{A_s(i)} + \frac{Q_{rt}(i)}{A_s(i)} = 0, \text{ for } i = 1,2,3 \dots n_s \quad (2)$$

The energy balance for the attic air control volume included mass transfer by ventilation and infiltration; heat energy transfer via convection from the ducts, trusses, and all surfaces bounding the attic control volume (Ober & Wilkes, 1997), Eq. 3.

$$\sum_{i=1}^{n_s} [A_s(i)q_{ci}(i)] + Q_{vent} + Q_{cD} + Q_{ct} + Q_L = 0 \quad (3)$$

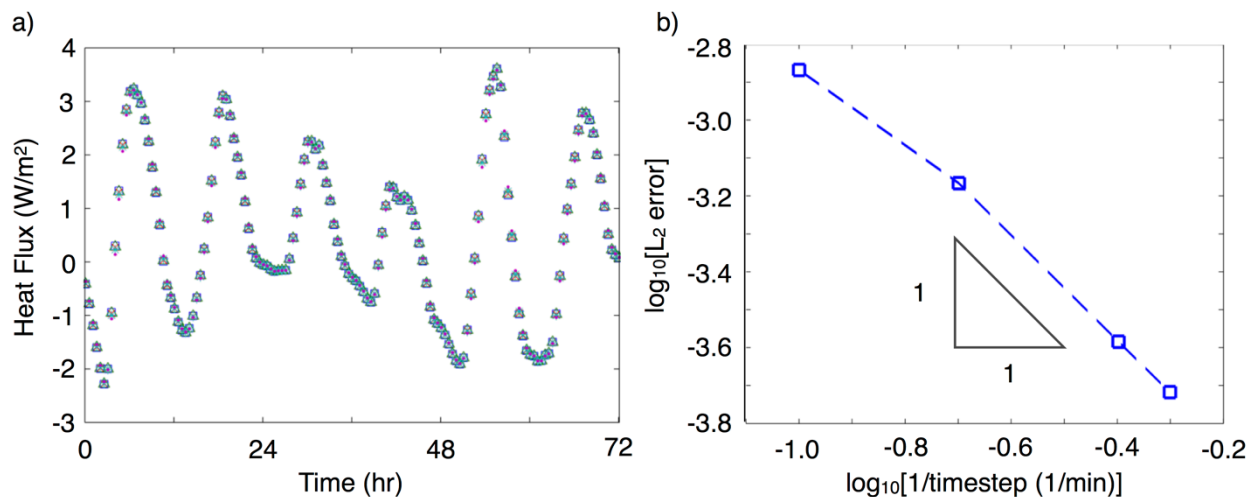
### Solution Procedure

In order to deploy FATM, folders containing the general input, construction, geometric configuration and climate input files are uniquely created for each of the 144 scenarios. The general input file is the base for each simulation (Fontanini et al., 2015). It contains the location of the construction files for the attic surfaces, solving tolerances, time steps, output frequencies. This file also contains information about the longitudinal and latitudinal location of the attic structure, its orientation, time zones, and initial temperatures of attic surfaces and components (Fontanini et al., 2015). The nonlinear solvers in FATM solve the governing equations to a residual relative tolerance of  $2.0 \times 10^{-4}$ . The roof structures are configured to contain neither ductwork systems nor trusses, are uninhabited, and the temperature below the attic floor held at a constant 20°C. The View3D geometry files contain the locations of vertices and surfaces that compose each roof structure. We refer the reader to the View3D instruction manual by J. DeGraw for a description of properly notating vertices and planar surfaces (Walton, 2009). The TMY3 and FTMY climate files serve as the weather input for the FATM program. The output quantities (surface temperatures, surface heat fluxes and attic air temperatures) are stored in a single output CSV file. The output frequency of each quantity of interest is once every 5-minute time step. Based on the outputs of FATM (heat flux, attic air temperature, and surface temperatures), the quantities of interested were calculated based on the governing equations, Eq.

1 – 3. Given the correct format of each file and number of surfaces the FATM program takes approximately 5 minutes to run the program for a full year<sup>8</sup>.

### Solution verification

Since FATM solves a set of ordinary differential equations in time, the choice of time step used is crucial. We perform temporal convergence analysis by performing and comparing simulations using different time steps to simulate a full year of attic performance. We consider time steps of 1 minute, 2 minutes, 2.5 minutes, 5 minutes, and 10 minutes. When temporal convergence is ensured, the results as time step is decreased should not change. This is clearly seen in Figure 3a, where there is little difference between the four time steps. The  $L_1$  error, Fig. 3b, which represents the error (normalized difference) between different numerical solutions converges at an approximate rate of 1.23 which is consistent with the numerical scheme implemented in FATM. An  $L_1$  error of 0.07% between the 5-minute and the 1-minute timestep was determined to be sufficiently small for this analysis, and a 5-minute timestep is used for all the simulations. The chosen time step also resulted in a Fourier number less than 3 for all the construction components which further implied an acceptable choice of timestep.



<sup>8</sup> Only non-leap years are considered by the FATM program.



Figure 3: a) Results using various time steps for the gable ended case and TMY weather data shows temporal convergence. b)  $L_1$  error between the 1-minute timestep and the 2-minute, 2.5 minute, 5-minute, and 10-minute timesteps.

### Quantities of Interests

In this study, several quantities of interest are considered to assess thermal performance: thermal loads, attic air temperature, and peak roof deck temperatures<sup>9</sup>. Specifically, this work analyzes these quantities during extreme points of the heating and cooling seasons. The attic air temperature and roof deck temperatures are direct outputs from the governing equations of the FATM program. The peak roof deck temperature of each day is collected into distributions during the cooling season. Then shifts in the mean and changes in standard deviation of these distributions are further analyzed. For thermal loads, the heating and cooling loads are calculated by integrating the heat flux on the ceiling facing the conditioned space during the heating and cooling seasons defined by table 3, Eq. 4 and Eq. 5.

$$Q_{CL} = A_{ceiling} \int_{iDOY_{start}^{(CL)}}^{iDOY_{end}^{(CL)}} q_{ceiling}(t) dt \quad \text{for } q_{ceiling}(t) > 0 \quad (4)$$

$$Q_{HL} = A_{ceiling} \int_{iDOY_{start}^{(HL)}}^{iDOY_{end}^{(HL)}} q_{ceiling}(t) dt \quad \text{for } q_{ceiling}(t) < 0 \quad (5)$$

Once the governing equations are numerically solved in FATM, a discrete vector of heat fluxes on the outside of the attic floor is outputted in increments of the simulation timestep. Two integration methods, the midpoint method, Eq. 6a and 6b, and trapezoidal method, Eq. 7a and 7b, were tested to ensure the heat flux values are integrated accurately.

$$Q_{CL} = \Delta t \sum_{i=1}^{n_{steps}^{(CL)}} q_{ceiling}(i) \quad \text{for } q_{ceiling}(t) > 0 \quad (6a)$$

$$Q_{HL} = \Delta t \sum_{i=1}^{n_{steps}^{(HL)}} q_{ceiling}(i) \quad \text{for } q_{ceiling}(t) < 0 \quad (6b)$$

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<sup>9</sup> We note that full characterization of thermal performance is not limited to these quantities, but we chose these quantities as representative of the thermal performance.

$$Q_{CL} = \frac{\Delta t}{2} \sum_{i=1}^{n_{steps}^{(CL)}} [q_{ceiling}(i+1) + q_{ceiling}(i)] \quad \text{for } q_{ceiling}(t) > 0 \quad (7a)$$

$$Q_{HL} = \frac{\Delta t}{2} \sum_{i=1}^{n_{steps}^{(HL)}} [q_{ceiling}(i+1) + q_{ceiling}(i)] \quad \text{for } q_{ceiling}(t) < 0 \quad (7b)$$

The difference between the yearly heating and cooling loads between the two methods was 1.79%. We use the midpoint method to calculate the heating and cooling loads for the rest of the study.

## 2.4 Results

The results are separated into three sections: cooling season, heating season, and peak roof deck temperatures. Based on these quantities, some general observations are made from the data regarding the most and least affected attic geometry and city. For each of the six geographic locations, the heat flux through the ceiling, attic air temperatures, and total cooling loads for the entire cooling season are shown below, Figures 4 – 6. For each of the six geographic locations the heat flux through the ceiling, attic air temperatures, and total heating loads for the entire heating season are shown below, Figures 7 – 9.

### Cooling Season

Figure 4a represents the heat fluxes through the attic floor during the hottest week of the cooling season in Atlanta, Georgia under current climate conditions (TMY3). The cyclic pattern corresponds to the rising and setting of the sun. Due to the similar light-weight construction, the heat flux profiles all roughly peak around the same time of day for all the cities, table 4. It was also seen in the future climate scenarios that these times for peak loads did not change significantly for the cooling season. From figure 4a it is also seen that the gable and hip roofs behave similarly. The combination and mansard roofs behave similarly and have the higher heat flux peaks compared to other geometric configurations. The flat roofs have the lowest heat fluxes

of all the geometries investigated in this study. Climatic conditions, i.e. FTMY data, only showed an increase the heat flux during the day, figure 4b. While a limited set of cases are shown in figure 4, these conclusions held true across all locations, current climatic conditions, and future climatic scenarios.

*Table 4: The average time of day for peak loads from the attic space for current TMY3 weather data during the cooling season.*

City	Gable	Hip	Flat	Combination	Mansard
<b>Atlanta</b>	3:25PM	3:26 PM	3:30 PM	3:02 PM	3:03 PM
<b>Baltimore</b>	1:37 PM	1:35 PM	1:48 PM	1:18 PM	1:18 PM
<b>Los Angeles</b>	12:54 PM	12:53 PM	12:52 PM	1:01 PM	12:58 PM
<b>Minneapolis</b>	3:15 PM	3:15 PM	3:33 PM	2:43 PM	2:49 PM
<b>Phoenix</b>	3:07 PM	3:07 PM	3:01 PM	2:46 PM	2:48 PM
<b>Seattle</b>	2:38 PM	2:38 PM	2:47 PM	2:33 PM	2:34 PM

Figure 5 represents the evolution of attic air temperature for all geometric configurations during the hottest weeks of the cooling season in Atlanta, Georgia under all four climatic conditions and all the attic geometries. Overall there is a general increase in attic air temperatures as the climatic conditions evolve from current to future climatic conditions. Even though the flat roofs were seen to have the lowest heat flows through the ceiling in figure 8, the flat roof has the highest attic air temperatures, Fig. 9, in comparison to the other attics. This contrast may be due to the different venting configuration soffit/soffit compared to the soffit/ridge for the other attics. Other than the flat roof the average attic air temperatures are roughly the same across all other geometries. The general trends followed similar trends for all other cities and climate scenarios.

Figure 6 is organized by geographic location, each graph depicts cooling loads for both current (TMY3) and future (FTMY) climatic conditions, where the FTMY climatic conditions are labeled by carbon dioxide levels ( $\text{CO}_2$ ). From this data, there exists a general increase of cooling loads as climate conditions change from current to future conditions. From these cooling loads the relative increases from the current TMY3 data files we computed for all future climate

scenarios, table 5. From these relative increases in cooling loads, the most and least affected attic geometries and cities are determined. Flat roofs are the geometric structure most affected by future climatic conditions, while the combination and mansard roofs are least affected. Minneapolis, MN and Phoenix, AZ are the most and least affected cities, respectively as climatic conditions evolve. The minimum percent increase overall the data occurs in Phoenix, AZ with the combination roof under FTMY, low CO<sub>2</sub> levels at 11.59%. The maximum percent increase overall the data occurs in Minneapolis, MN with the flat roof under FTMY, high CO<sub>2</sub> levels at 58.13%.

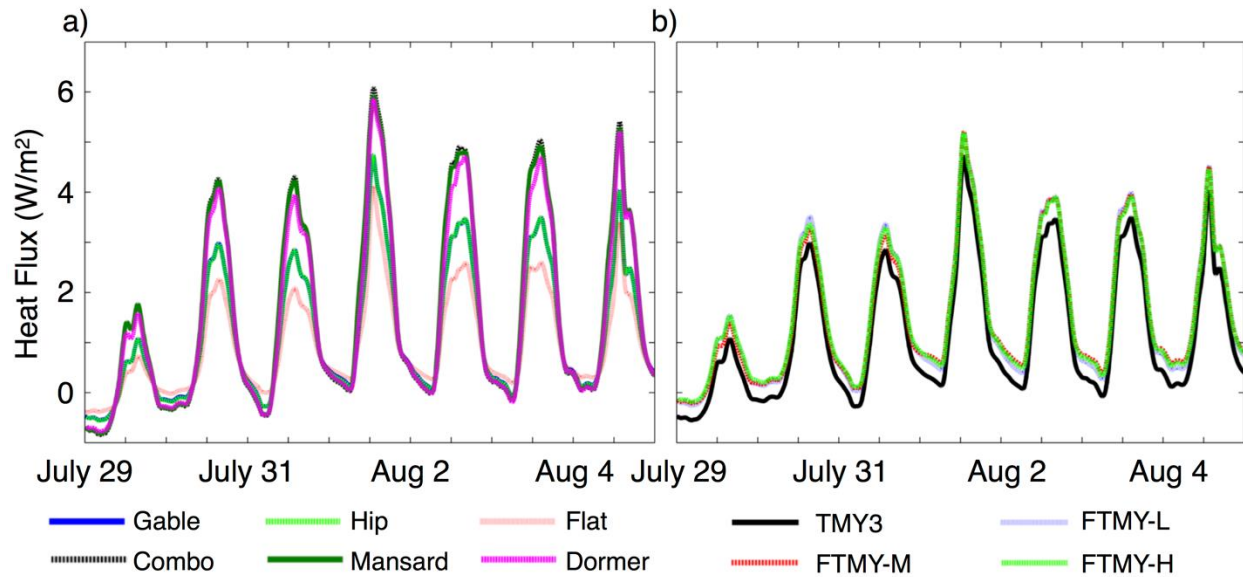


Figure 4: a) Typical temporal heat flux profile for Atlanta, GA during the heating season for all the attic geometries under TMY3 climatic conditions, and b) typical temporal heat flux profile for the gable ended roof geometry in Atlanta, GA for current climate condition and future climate scenarios.

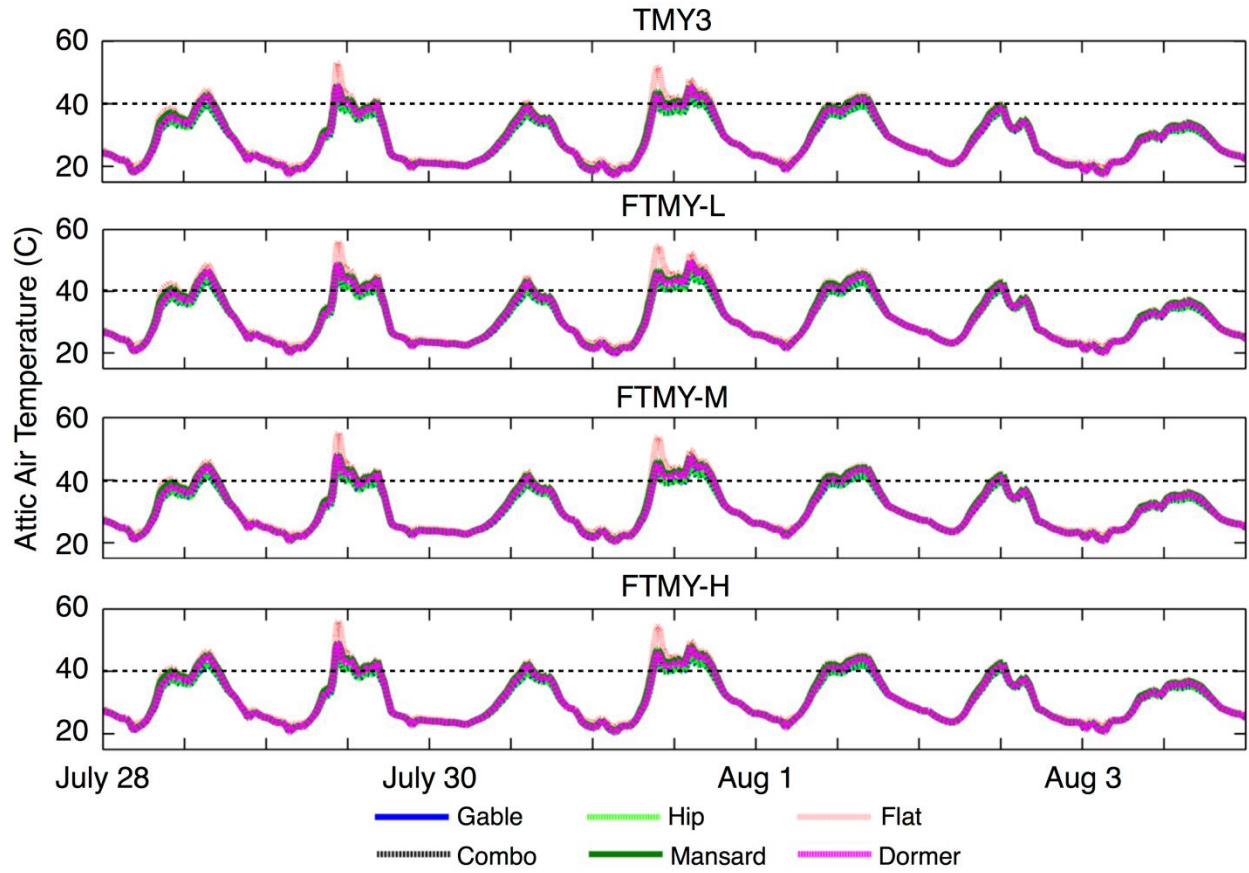


Figure 5: Attic Air Temperature Evolution from TMY3 to FTMY climatic conditions during the cooling season.

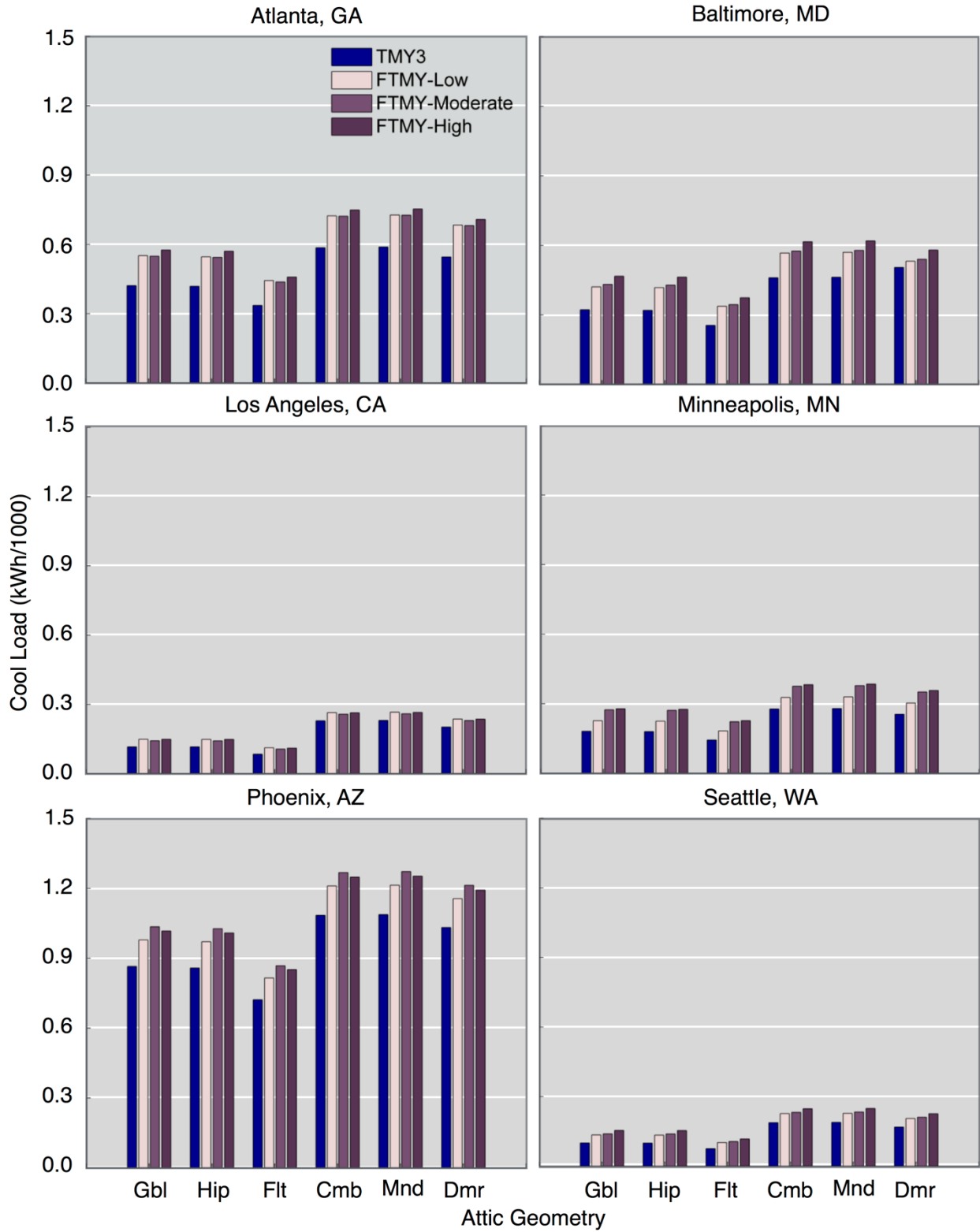


Figure 6: Cooling loads for each attic geometry and climatic scenario by geographic location.

Table 5: Table of minimum and maximum relative increases in cooling loads based on the future climate scenarios.

City	Gable (%)	Hip (%)	Flat (%)	Combination (%)	Mansard (%)	Dormer (%)
<b>Atlanta</b>	30.2-36.6	29.9-36.3	30.2-36.5	23.3-27.9	23.4-28.0	24.8-29.7
<b>Baltimore</b>	23.3-31.0	23.3-30.8	24.5-32.0	18.8-25.3	18.8-25.3	20.2-26.8
<b>Los Angeles</b>	22.9-28.1	22.6-27.8	26.7-33.6	12.6-15.5	12.7-15.5	14.0-17.2
<b>Minneapolis</b>	25.2-53.7	25.0-53.4	27.3-58.1	17.9-37.7	17.9-37.7	19.0-40.3
<b>Phoenix</b>	13.1-19.7	13.1-19.7	12.9-20.2	11.6-16.9	11.6-17.0	12.0-17.5
<b>Seattle</b>	34.6-54.1	34.4-53.9	34.6-54.6	20.5-31.9	20.5-31.9	22.2-34.4

### Heating Season

Figure 7a represents the heat fluxes through the attic floor during the coldest week of the heating season in Minneapolis, Minnesota under current climate conditions (TMY3). The cyclic pattern corresponds to the rising and setting of the sun. Due to the similar light weight construction, the heat flux profiles all roughly peak around the same time of day approximately 2:31PM – 7:06 AM for all the cities, table 6. It is also seen in the future climate scenarios that these times for peak loads did not change significantly for the heating season. From figure 11a it is also seen that the gable, hip roofs, and flat behave similarly. The combination, mansard, and gable-dormer roofs behave similarly and have low heat flux peaks compared to other geometric configurations. The flat roofs have the lowest heat fluxes of all the geometries investigated in this study. Climatic conditions, i.e. FTMV data, showed an increase in the heat flux during the day, figure 7b. While a limited set of cases are shown in figure 7, these conclusions held true across all locations, current climatic conditions, and future climatic scenarios.

Table 6: The average time of day for peak loads from the attic space for current TMY3 weather data during the heating season.

City	Gable	Hip	Flat	Combination	Mansard	Dormer
Atlanta	6:55 AM	6:54 AM	6:58 AM	6:54 AM	6:53 AM	6:53 AM
Baltimore	2:31 AM	2:31 AM	3:24 AM	2:36 AM	2:38 AM	2:37 AM
Los Angeles	5:35 AM	5:35 AM	5:50 AM	5:42 AM	5:41 AM	5:40 AM
Minneapolis	4:36 AM	4:36 AM	6:18 AM	5:46 AM	5:47 AM	4:46 AM
Phoenix	6:58 AM	6:59 AM	6:56 AM	7:02 AM	7:03 AM	7:06 AM
Seattle	5:07 AM	5:07 AM	6:19 AM	5:14 AM	5:16 AM	5:14 AM

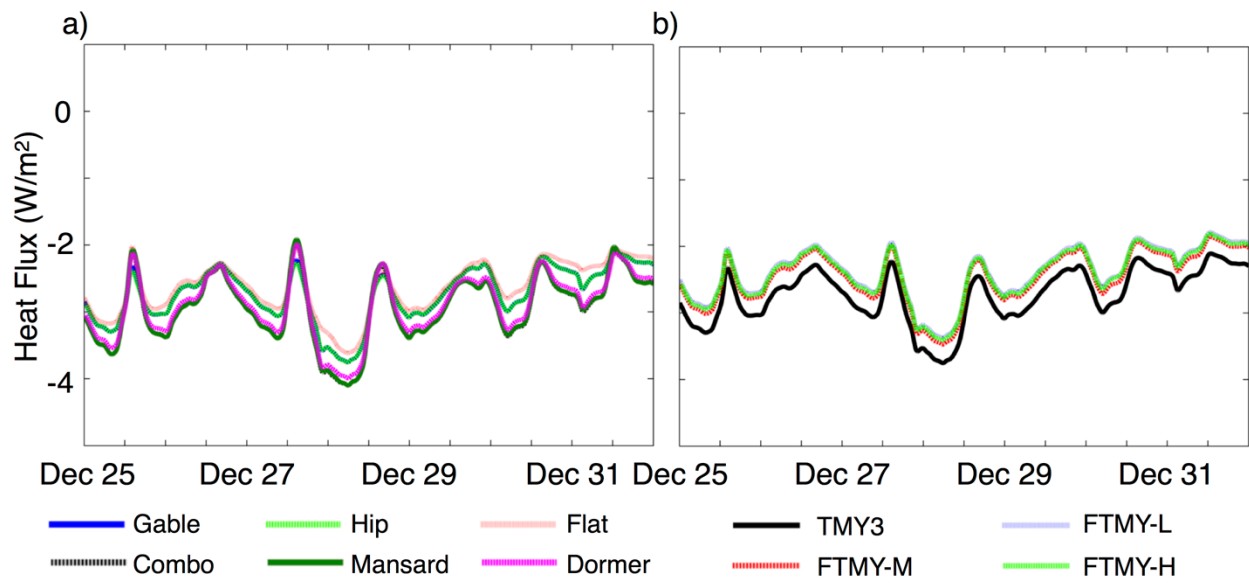


Figure 7: a) Typical temporal heat flux profile for Minneapolis, MN during the heating season for all the attic geometries under TMY3 climatic conditions, and b) typical temporal heat flux profile for the gable ended roof geometry in Minneapolis, MN for current climate condition and future climate scenarios.



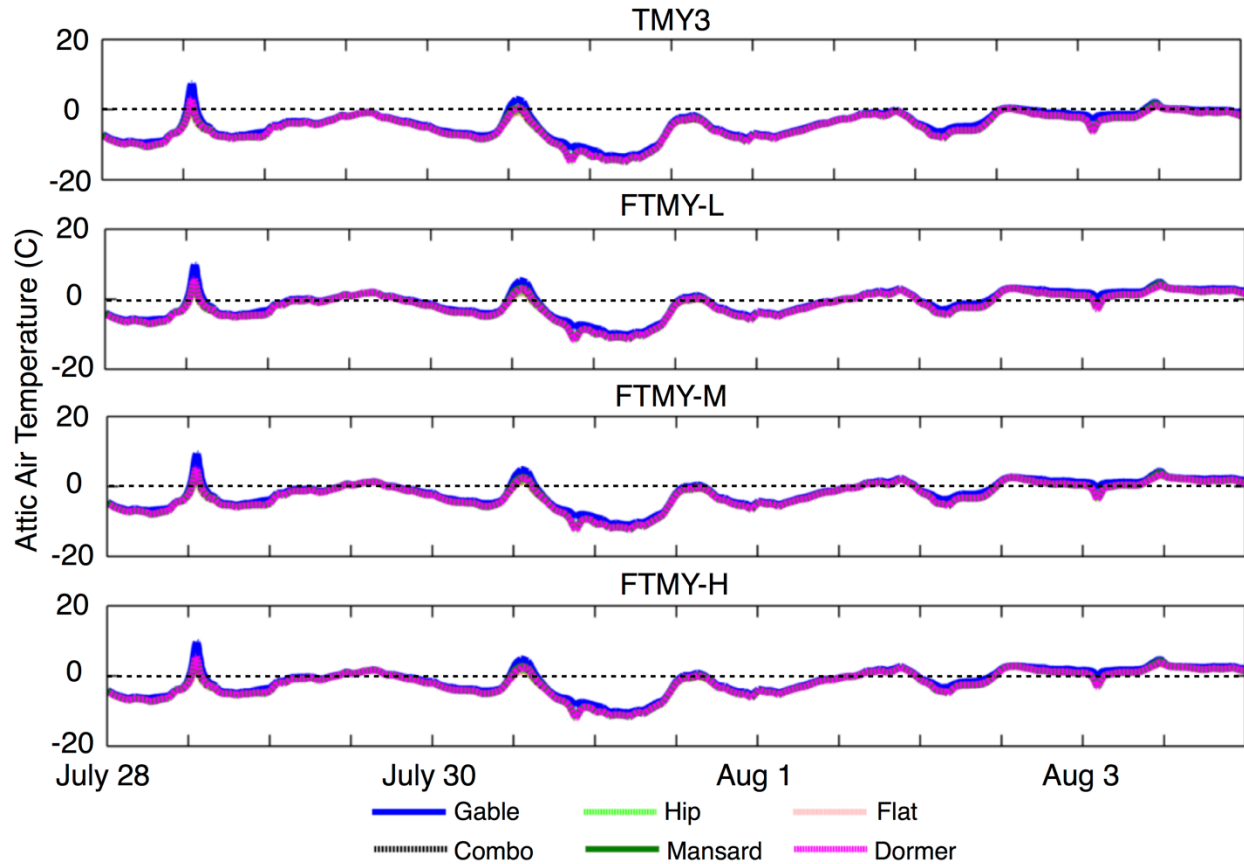


Figure 8: Attic air temperature comparison Minneapolis, MN as climatic condition change during the heating season.

Figure 8 represents the evolution of attic air temperature for all geometric configurations during the coldest week of the heating season in Minneapolis, Minnesota under all four climatic conditions and all the attic geometries. Overall there is a general increase in attic air temperatures as the climatic conditions evolve from current to future climatic conditions. Once again the flat roof is slightly warmer than the other geometries selected in this study. Other than the flat roof the average attic air temperatures are roughly the same across all other geometries. This general trend is followed for all other cities and climate scenarios.

Figure 9 is organized by geographic location, each graph depicts cooling loads for both current (TMY3) and future (FTMY) climatic conditions, where the FTMY climatic conditions

are labeled by carbon dioxide levels (CO<sub>2</sub>)<sup>10</sup>. From this data, there exists a general decrease of heating loads as climate conditions change from current to future conditions. From these heating loads, we computed the relative increase over current TMY3 data, table 7. From these relative increases in heating loads the most and least affected attic geometries and cities are determined. Flat roofs are the geometric structure most affected by future climatic conditions, while the combination and mansard roofs are least affected. Los Angeles, CA and Baltimore, MD are the most and least affected cities, respectively as climatic conditions evolve. The minimum percent decrease overall in the data occurs in Baltimore, MD with the combination roof under FTM<sub>Y</sub>, moderate CO<sub>2</sub> levels at 8.20%. The maximum percent decrease overall in the data occurs in Los Angeles, CA with the hip roof under FTM<sub>Y</sub>, high CO<sub>2</sub> levels at 35.02%.

*Table 7: Table of minimum and maximum relative decreases in heating loads based on the future climate scenarios.*

<b>City</b>	<b>Gable</b>	<b>Hip</b>	<b>Flat</b>	<b>Combination</b>	<b>Mansard</b>	<b>Dormer</b>
<b>Atlanta</b>	10.7-14.1	10.7-14.1	11.3-14.6	9.8-13.0	9.8-13.1	9.8 -13.1
<b>Baltimore</b>	8.7-11.9	8.7-11.9	9.3-12.90	8.2-11.2	8.3-11.3	8.7-11.4
<b>Los Angeles</b>	18.1-29.2	18.1-35.0	21.9-33.9	14.9-24.5	15.1-24.8	15.0-22.6
<b>Minneapolis</b>	9.9-11.9	9.9-11.9	10.5-12.3	9.4-11.4	9.5-11.5	9.7-11.5
<b>Phoenix</b>	13.8-22.8	13.9-22.8	17.6-26.2	11.2-19.6	11.4-19.8	11.2-19.3
<b>Seattle</b>	10.6-15.4	10.5-15.4	9.6-17.4	9.7-14.3	9.9-14.5	9.5-14.5

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<sup>10</sup> It is important to note that low, moderate, and high CO<sub>2</sub> levels do not necessarily translate to low, moderate and high temperature increases and therefore heat fluxes.

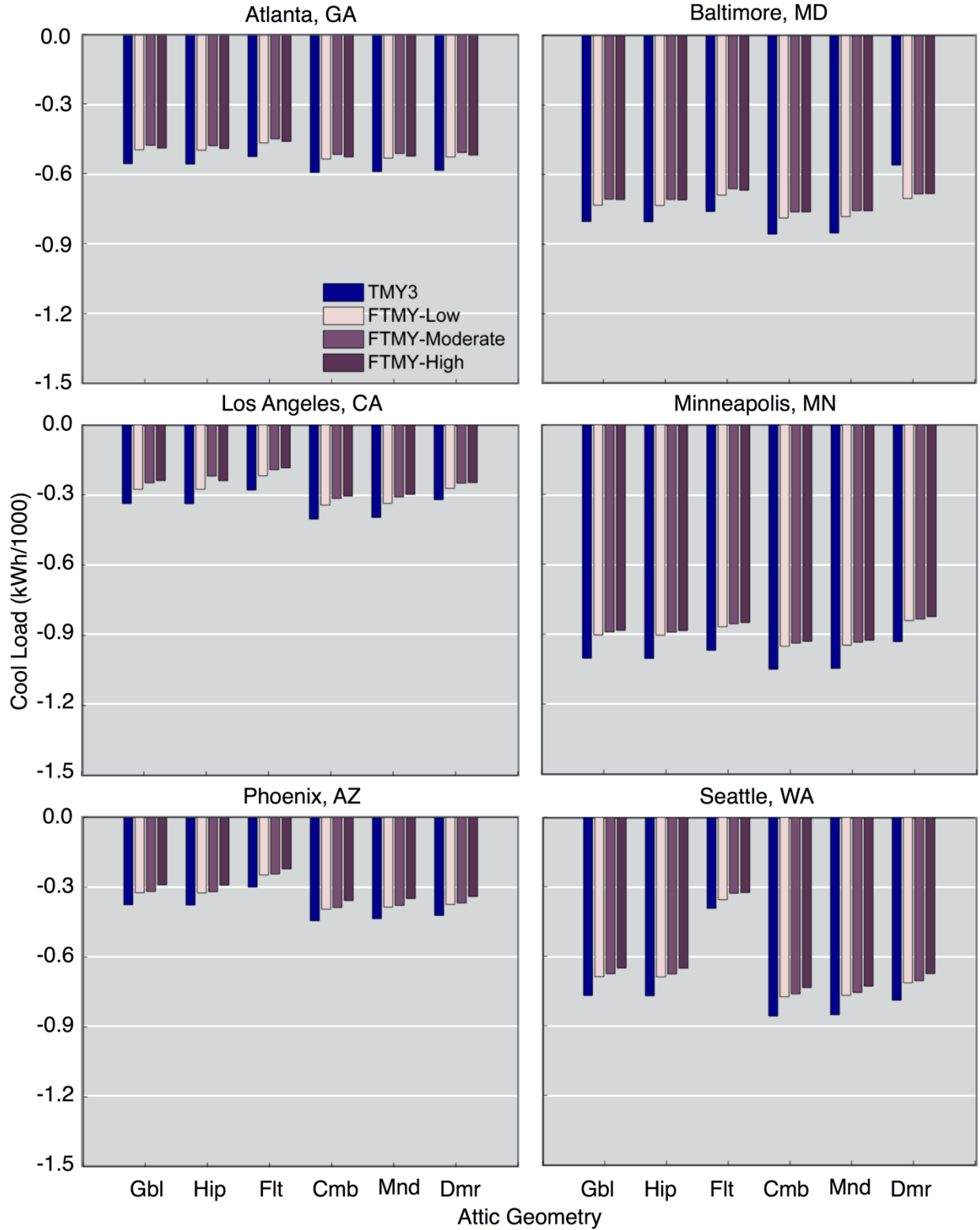


Figure 9: Heating loads for each attic geometry and climatic scenario by geographic location.

### Peak Roof Deck Temperatures

Roof deck temperatures are an adequate way to analyze the outside radiative surface properties roof decks. From the data, increasing temperatures may equate to an increase in peak roof deck temperatures. This increase may contribute to degradation of the asphalt shingles. The daily peak roof deck temperature is collected into a distribution over the cooling season for each attic geometry and climate scenario. The mean and standard deviations of this data are shown in table 8. Figure 10 shows the combined peak roof deck temperatures for all roof types in different cities for the current and future climate scenarios. The majority of the outliers shown in figure 10 seems to be overly cloudy and cool days during the cooling season in each of the cities. Phoenix, AZ has the highest peak roof deck temperatures with the smallest spread in the distribution. Minneapolis, MN has the lowest peak roof deck temperatures with the smallest spread in distribution. Based on the relative changes in the mean peak daily roof deck temperatures, Baltimore is the city most affected (6.3% shift in the mean) and Los Angeles is the city least effected (2.4% shift in the mean).

*Table 8: Geometry combined table of mean and standard deviation of the daily peak roof deck temperatures for each city.*

<b>Location</b>	<b>TMY3</b>		<b>FTMY</b>	
	<b>Mean (C)</b>	<b>STD (C)</b>	<b>[Min – Max] mean (C)</b>	<b>[Min – Max] STD (C)</b>
<b>Atlanta</b>	71.9	12.1	74.3 – 74.9	11.8 – 11.9
<b>Baltimore</b>	66.3	11.6	69.0 – 70.5	11.6 – 11.6
<b>Los Angeles</b>	65.4	6.3	66.7 – 67.0	6.4 – 6.4
<b>Minneapolis</b>	59.7	12.5	61.2 – 63.4	12.3- 12.5
<b>Phoenix</b>	87.3	6.1	89.1 – 89.6	6.0 – 6.1
<b>Seattle</b>	60.3	12.7	62.1 – 62.7	12.8 – 12.8

When individual roof deck shapes are investigated, a few other conclusions from the data can be made. Based on these results, there is roughly a 3-4°C range in the mean daily peak roof

deck temperatures between all the different attic geometries in a given city. The results also showed that the hip roof has the highest mean peak roof deck temperatures across all the cities, where the flat roof construction has the lowest mean peak roof deck temperatures across all the cities. A maximum relative increase from the future climate scenarios for the mean peak roof deck temperatures was 6.79% for the flat roof located in Baltimore. A minimum relative increase from the future climate scenarios for the mean peak roof deck temperatures was 1.69% for the hip roof in Los Angeles.

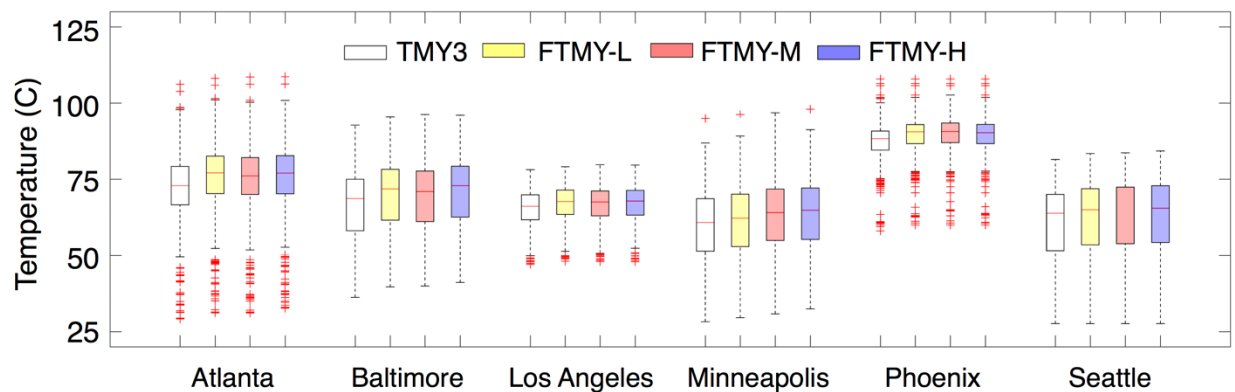


Figure 10: Attic geometry combined daily peak roof deck temperature distributions for the gable-ended roof structure by geographic location.

## 2.5 Discussion

### *Cooling Loads vs. Heating Loads*

There are some expected outcomes when examining the cooling loads. For example, Phoenix, AZ exhibits the highest cooling loads since it was the only city located in climate zone 2, as defined by ASHRAE 90.1. However, it was not expected for cities in similar climate zones to have vastly different cooling load values. Even though Atlanta, GA and Los Angeles, CA are in the same zones, they have different cooling loads requirements; similarly, for Baltimore, MD and Seattle, WA. Additionally, Minneapolis, MN, exhibits larger cooling loads than both Los Angeles, CA and Seattle, WA, despite being in a colder climate zone. This suggests that

humidity or moisture levels play a significant role in load values. During the cooling season, it was found that flat roofs are the geometric structure most affected by future climatic conditions, while the combination and mansard roofs are least affected. Minneapolis, MN and Phoenix, AZ are the most and least affected cities, respectively as climatic conditions evolve.

Similarly, there are some expected outcomes when examining the heating loads. Phoenix, AZ and Minneapolis, MN have the lowest and highest heating loads, respectively, strictly based off geographic location. On the other hand, while Atlanta, GA and Los Angeles, CA are both in the same climate zone, they have different heating loads requirements; albeit not as drastically different as for the cooling loads. Similar to the attic structures most and least affected during the cooling season, it was determined that during the heating season the flat and combination/mansard roofs are most and least affected geometric configurations, respectively. In terms of location, Los Angeles, CA and Baltimore, MD are the most and least affected cities, respectively.

#### *Peak Roof Deck Temperatures*

Traditionally in attic thermal research, radiative thermal properties are ranked above thermal insulation properties (Bianchi et al., 2007). However, as shown in the section with results for the peak roof deck temperatures, radiative surface properties play an important role in the thermal characteristics of an attic structure. This is particularly true in places that are located in warmer climates such as Atlanta, Los Angeles, and Phoenix. Exploring how changing the roof deck materials (the material properties) affects the roof deck temperature is an avenue that is worth investigating.

In an energy conscious society, identifying ways to decrease energy consumption and preserve natural resources is of the utmost importance. This research shows that an increase in

temperature as a result of changing climatic conditions results in an increase of thermal loads, attic air temperatures, and peak roof deck temperatures. All of these elements combined indicate that the energy demands of both residential and commercial properties will steadily increase.

## **2.6 Conclusions and future research avenues**

This paper investigates the impacts of future climate data on the thermal performance of different attic geometries for several standard roof constructions. This paper is part 1 of a 2-part study that includes different cool roofs (cool shingles and metal roofing). We simulate the thermal performance of six different roof geometries under six geographically diverse cities in the US for current, and three future climate scenarios. We identify trends of heating and cooling loads that these roofs will exhibit. The analysis also enables identification of geographical regions where energy usage in attics is more sensitive to changes in weather. We extend this analysis in the next paper, where we consider the additional effect of asphalt shingles, cool shingles, and metal roofs on attic performance. As sustainable products, materials, and structures are being developed, we envision such analysis would prove valuable to understand and sustainably adapt to the effects of changing climatic conditions.

This analysis suggests several additional avenues of research. These include investigating the effect of air ducts, cathedralized ceiling designs, different venting configurations and net free area, the use of different attic insulation materials including materials with large thermal mass, and setback schedules in the residential building on attic thermal performance in current and future climate scenarios. Such analysis will lead to a more complete picture of the thermal performance of attic spaces and will result in more efficient and sustainable designs.

## 2.7 Acknowledgements

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## 2.8 Nomenclature

$A_s(i)$  – Surface area of the discrete surface  $i$  used in the view factor calculation, for  $i = 1,2$

$A_{ceiling}$  – Surface area the ceiling facing the occupied space

$iDOY_{start}^{(CL)}$  – The integer day of year that the cooling load starts for a particular city

$iDOY_{end}^{(CL)}$  – The integer day of year that the cooling load ends for a particular city

$iDOY_{start}^{(HL)}$  – The integer day of year that the heating load starts for a particular city

$iDOY_{end}^{(HL)}$  – The integer day of year that the heating load ends for a particular city

$n_{steps}^{(CL)}$  – The number of timesteps in the cooling season for a particular city

$n_{steps}^{(HL)}$  – The number of timesteps in the heating season for a particular city

$Q_{cD}$  – The energy transfer convected from the air ducts

$Q_{rD}(i)$  – The radiation exchange between the ducts and surface  $i$

$Q_{rt}(i)$  – The radiation exchange between the trusses and surface  $i$

$Q_{CL}$  – The cooling load

$Q_{ct}$  – The energy transfer convected from the trusses

$Q_{HL}$  – The heating load

$Q_L$  – The energy transfer from leakage in the air ducts

$Q_{vent}$  – The ventilation and infiltration energy transfer

$q_i(i)$  – The heat flux via conduction on the inside of surface  $i$

$q_{ceiling}$  – The heat flux through the ceiling facing the occupied space



$q_{ci}(i)$  – The heat flux via convection on the inside of surface i

$q_{co}(i)$  – The heat flux via convection on the outside of surface i

$q_{moist}(i)$  – The absorption/desorption heat flux on the inside of surface i

$q_o(i)$  – The heat flux by conduction on the outside of surface i

$q_{rj}(i)$  – The radiative heat flux from other standard surfaces on the inside surface i to surface j

$q_{ro}(i)$  – The heat flux via radiation on the outside of surface i

$q_s(i)$  – The solar radiation incident on the outside of surface i

$\alpha(i)$  – The solar absorptivity on the outside of surface i

$\Delta t$  – The simulation timestep

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## CHAPTER 3

### CONCLUSIONS AND FUTURE WORK

#### 3.1 Summary of findings

Climatic changes have caused an increase in average temperatures across the globe. As a result of this increase, buildings systems are experiencing a concurrent increase in cooling loads and decrease in heating loads. The result from this work, as it pertains to attic spaces, further supports this trend. Furthermore, an increase in mean temperatures also results in slightly higher attic air and peak roof deck temperatures, as supported by findings from this work. During the cooling season, we found that across all geographical locations and geometric configurations there was a significant increase in cooling load requirements. The percent increase ranged from 11.59% - 58.13% as climatic conditions evolved from current (TMY3) to future (FTMY) climate scenarios. Also, during the heating season, the percent increase from TMY3 to FTMY climatic scenarios was found to be within in the range of 8.20% - 35.02%. The peak roof deck temperatures, according to our results, showed an increase of 3 – 4 °C across all locations and configurations. We also found that the structure most and least affected for both the heating and seasons were the flat and combination/mansard roofs, respectively. In terms of location, during the cooling season the city most affected by future climate trends was Minneapolis, MN, while Phoenix, AZ was the least affected. The heating season showed that the most and least affected cities were Los Angeles, CA and Baltimore, MD, respectively. Overall, despite geometric configuration and geographical location, this work shows continuous increase in energy demands for residential and light commercial buildings.

### 3.2 Implications of findings

The implications from this work lead to the solution of adding insulation levels within the attic floor to mitigate the effects of future climate trends; specifically as it pertains to cooling loads. By installing additional levels of insulation within the attic floor, it will change the overall effective U-value of the attic structure. The effective U-value, denoted  $U_{eff}$ , numerically characterizes the rate of heat transfer for a component or assembly, and is the reciprocal of its R-value, i.e.  $U_{eff} = \frac{k}{L} [\frac{W}{m^2K}]$ , where ‘k’ is the thermal conductivity and ‘L’ is the thickness of the insulation. Therefore, by adding layers of insulation, it should decrease the rate of heat being transferred throughout the attic structure into the enclosed occupied space and mitigate the cooling load requirements of the HVAC system. This solution, however, will vary based on geographical location along with geometric configuration. The current insulation levels and corresponding  $U_{eff}$  values, across all geometric configurations by geographical location under all climatic scenarios are as followed: Atlanta, GA; Los Angeles, CA; and Phoenix, AZ have insulation levels of 0.30[m] with a corresponding  $U_{eff}$  of approximately 0.19 W/m<sup>2</sup>K; Baltimore, MD and Seattle, WA are approximately 0.31[m] and 0.15[W/m<sup>2</sup>K]; and finally, Minneapolis, MN has the highest insulation levels of 0.41[m] with the lowest  $U_{eff}$  of 0.11[W/m<sup>2</sup>K]. Utilizing Newton’s method, we minimized the difference in current and future cooling loads<sup>11</sup> to find the new thickness of insulation required. Given the new ‘L’, we then calculate the new  $U_{eff}$  of the attic floor; finally  $\Delta U_{eff}$  is found by subtracting new  $U_{eff}$  values from the corresponding initial  $U_{eff}$  values. It is our suggestion that engineers, architects, contractors, and homeowners concerned with the impacts of future climate trends, install these additional levels of insulation in

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<sup>11</sup> The solution converged to a cooling load tolerance of 0.01[kWh].

order to mitigate the impacts of future climate trends<sup>12</sup>, table 9. The corresponding added  $U_{\text{eff}}$  values across all locations and configurations with respect to the added insulation levels are listed in table 10.

Table 9: Suggested additional insulation across all locations and configurations in order to mitigate the effects of future climate trends.

[m]	Atlanta	Baltimore	Los Angeles	Minneapolis	Phoenix	Seattle
<b>Gable</b>	0.10	0.12	0.07	0.21	0.07	0.06
<b>Hip</b>	0.11	0.12	0.07	0.21	0.07	0.06
<b>Flat</b>	0.13	0.16	0.10	0.27	0.09	0.08
<b>Combination</b>	0.08	0.08	0.04	0.14	0.06	0.05
<b>Mansard</b>	0.08	0.08	0.04	0.14	0.06	0.05
<b>Dormer</b>	0.08	0.09	0.04	0.15	0.06	0.05

Table10: Additional effective  $U$ -values associated with the additional levels of insulation.

[W/m <sup>2</sup> K]	Atlanta	Baltimore	Los Angeles	Minneapolis	Phoenix	Seattle
<b>Gable</b>	0.07	0.04	0.06	0.04	0.06	0.04
<b>Hip</b>	0.07	0.04	0.06	0.04	0.06	0.04
<b>Flat</b>	0.08	0.05	0.07	0.05	0.07	0.05
<b>Combination</b>	0.06	0.03	0.05	0.03	0.05	0.03
<b>Mansard</b>	0.06	0.03	0.05	0.03	0.05	0.03
<b>Dormer</b>	0.06	0.03	0.05	0.03	0.06	0.03

Recalling the conclusions drawn from this research, the flat and mansard attic configurations are the most and least sensitive attic structures during the cooling season, respectively. Corresponding to this conclusion, we see from table 9 that the flat roofs require the most additional levels of insulation while the combination and mansard attic geometries require the least, regardless of geographical location. Furthermore, the city's most and least sensitive to climate change Minneapolis, MN and Phoenix, AZ also require proportional levels of added insulation. That is to say that Minneapolis, MN requires the most additional levels of insulation across all geographical locations; while Phoenix, AZ requires the least. The changes in  $U_{\text{eff}}$

<sup>12</sup> Specifically, the cooling loads resulting from the FTMY-moderate CO<sub>2</sub> climatic scenario in all geographical locations.



values, given in table 10, show a similar range amongst geographical locations with the same starting  $U_{\text{eff}}$ , e.g. Atlanta, Los Angeles, and Phoenix. Again, the flat and mansard roofs have highest and lowest  $U_{\text{eff}}$  values than the rest of the geometries, respectively. Atlanta, GA and Seattle, WA have the highest and lowest  $U_{\text{eff}}$  across all locations, respectively.

### **3.3 Recommendations for future work**

This work primarily focused on the impacts of future climate trends on six unique geometric configurations and thus the combined influence on the thermal characteristics attic envelopes. However, there are many other factors that affect the thermal performance of attic structures such as: the presence of trusses, air ducts, and HVAC systems, along with ventilation schemes, vaulted ceilings, etc. Investigating the impacts of these factors would be a possible research avenue for interested engineers and scientists. Additionally, given that the TMY3 datasets include climatic data for 1,020 various U.S. locations, it is recommended that the FTM Y datasets be extended to include more than 9 locations. The expansion of the FTM Y climatic datasets would assist in completing the analysis of these impacts on residential attic spaces in a variety of locations across the nation. Furthermore, we have already begun to explore the utilization of reflective roof deck materials or “cool roofs” and the alleviation this provides for cooling load requirements. This future analysis will then be compared to conventional constructed roof decks, done in this work, to understand how material properties coupled with climate trends impact attic thermal performance. Finally, we will continue to provide datasets from the implications of this work by providing values for added levels of insulation necessary to mitigate the effects of the remaining future climatic scenarios (FTMY-Low CO<sub>2</sub> and FTM Y-High CO<sub>2</sub>).

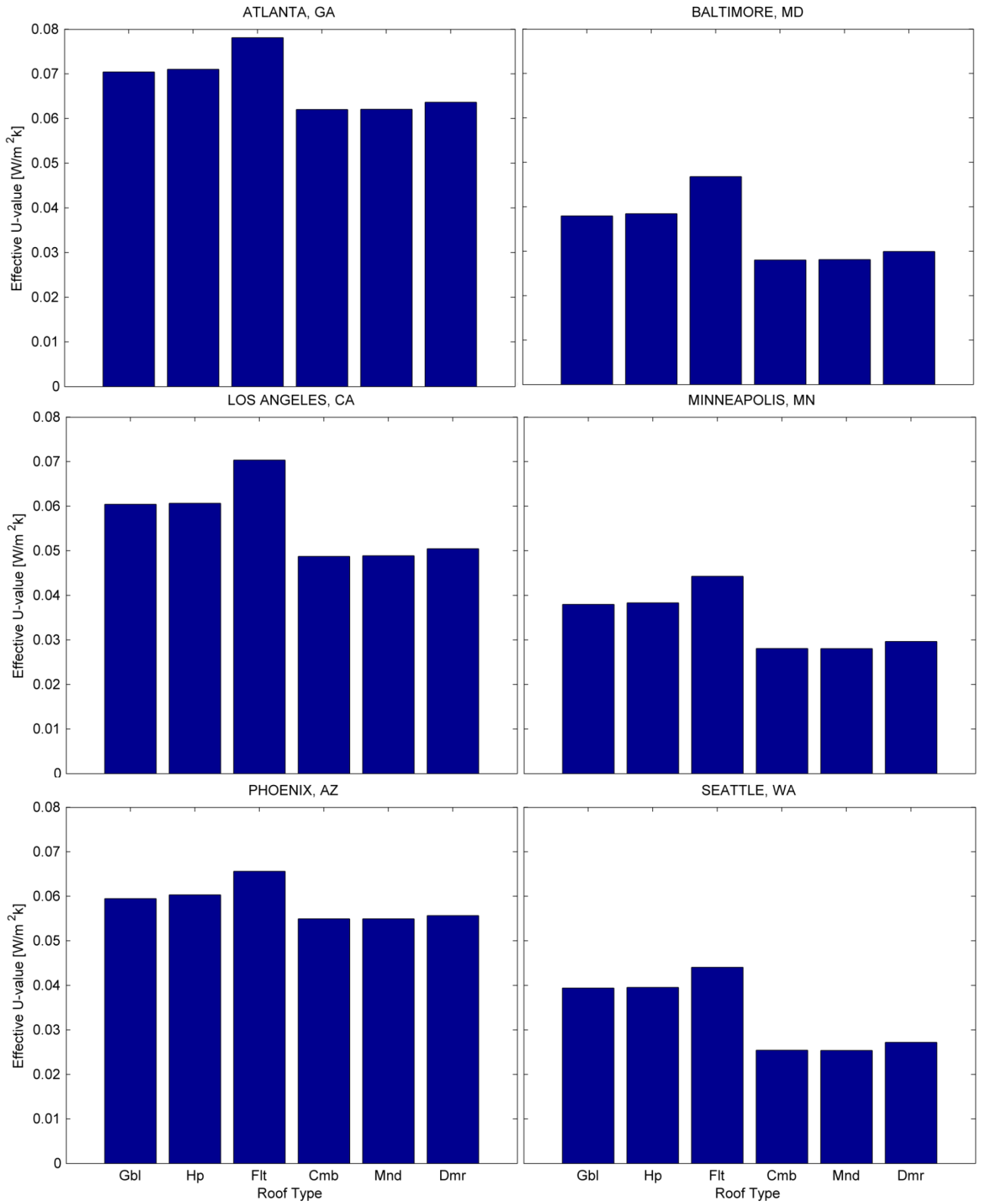


Figure 11: Change in effective U values ( $U_{eff}$ ) according to geographical location, graphical representation of Table 10.