FINAL REPORT

Effects of Sea Level Rise on Non-Motorized Transportation

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Rezvan Mohammadiziazi, MS, Graduate Research Assistant, University of Delaware
Ardeshir Faghri, PhD, Professor, University of Delaware

Prepared by:
Department of Civil & Environmental Engineering
University of Delaware
Newark, Delaware 19716

Prepared for:
Mid-Atlantic Transportation Sustainability Center (MATS-UTC)
Charlottesville, VA 22903

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16. Abstract

There are certain evidences that greenhouse gas emissions resulted from human activities have caused climate change. The intergovernmental panel for climate change (IPCC) has certified 0.2°C of increase in mean temperature per decade. Non-motorized transportation is considered as not only one of the major mitigation strategies to reduce the amount of greenhouse gas emissions but also as solution to bring safety, livelihood and health back to urbanized communities. This proves the importance of identifying facilities that are more vulnerable to the effects of climate change to start adaptations as early as possible. Sea level rise and the associated increase in frequency and intensity of storm surges and flooding incidences are perhaps among the most worrying consequences of climate change, especially for coastal areas.

Trails and bike routes are the non-motorized transportation facilities that are studied in this research. The distance of inundation (distance of trails and bike routes that will be under water), and the maximum depth of water on affected facilities are estimated by Geographic Information System (GIS) based analysis. The two measures then have been used to indicate the extent of vulnerability of facilities against sea level rise. Since there is a great amount of uncertainty around sea level rise (SLR), the analysis was done for three sea level rise projections. The result of this vulnerability assessment is reported as the level of service of each facility under different sea level rise projections.

Number of damaged trails under the medium SLR projection shows an increase of 56.76% compared to the number of damaged trails under low SLR scenario. This percent increases to 78.9% when the comparison was done between low and high SLR projections. To investigate the severity of different projections, we compared the total distance of damaged trails. Analysis showed that there will be 60.95% increase in mileage of damaged trails under medium SLR scenario compared to low scenario and this percent will be 90.3% if the comparison is done between the lowest and the highest SLR projections. The analysis results for the bike routes showed that under the low scenario bike routes will not vanish. However, the number of damaged bike routes will increase by 50% if sea level rises 6 feet rather than 4 feet. Also, there will be a 55.48% increase in distance of damaged bike routes when the comparison is made between medium and high sea level rise projections. These drastic changes prove that management corporations should plan their adaptation strategies for the worst-case scenario because the gap between low and high future sea level rise projections is considerable. In addition, all the analysis results prove that as sea level rise projection gets higher the number of trails with lower level of service increases.

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ABSTRACT

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Chapter 1

INTRODUCTION

1.1 Motivation

There are certain evidences that greenhouse gas emissions resulted from human activities have caused global warming and in general climate change. The intergovernmental panel for climate change (IPCC) has certified 0.2 °C of increase in mean temperature per decade. It is predictable that without mitigation efforts all around the world the rate of warming will be faster in future.

Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (Stocker, 2014). Several Studies show that the transportation sector contributes to 27 percent of U.S. greenhouse gas emissions, which is the major cause of climate change, so the Department of Transportation (DOT) clearly needs to think about emissions (Titus, 2002). As the transport sector is highly responsible for generating greenhouse gas emissions, many academic studies have addressed mitigation strategies such as using alternative fuels or more investments in public transportation. In addition, policies and regulations are making the mitigation process more convenient. For instance, clean air act which is a federal law, is designed to reduce air pollution on national level. From religious leaders (including Pope Francis) to many political leaders (including President Obama) have addressed the importance of pro-actively preparing the world and especially the future generations for these impacts. The

National Climate Assessment indicates that the impact of weather on human activities is inescapable and growing. In addition, climate change-related events such as sea level rise, extreme weather events, including heat waves, floods, and drought that have become more frequent and intense over parts of the country during the past 50 years will increase disruptions of infrastructure service in the future (Marchi, 2015). Non-motorized infrastructure such as sidewalks, bike lanes, shared use paths, parks and trails, can all be used for transportation, recreation, and fitness. These types of infrastructures have been shown to create many benefits for their users as well as the rest of the community (Garrett-Peltier, 2011). The effects of climate change either positive or negative on non-motorized transportation facilities should be studied for planning future mitigation strategies.

Non-motorized transportation is considered not only as one of the major mitigation strategies to reduce the amount of greenhouse gas emissions but also as solution to bring safety, livelihood and health back to urbanized communities. This proves the importance of identifying facilities that are more vulnerable to the effects of climate change to start adaptations as early as possible.

Three climate change derivatives have been identified to have the most effects on non-motorized transportation: sea level rise, increased frequency of intense precipitation and flooding, and increased temperature and heat waves. This study's focus is on the effects of sea level rise on trails and roadways with bike lane marking (bike routes) in Delaware.

1.2 Problem Statement

Direct impacts of climate change including exposure to weather extremes such as heatwaves and winter cold, increase in extreme weather events like floods, cyclones, storm surge drought, and sea level rise on civil infrastructure facilities such as roadways, bridges, tunnels and subways, rail stations, bus stations, parking lots, and airports have been studied by numerous scientists and engineers. However, there is lack of knowledge and analysis regarding the effects of climate change on pedestrian and bicycle facilities. Non-motorized transportation facilities such as pedestrian sidewalks, pedestrian and hiking trails, paths, bicycle paths, routes and trails, as well as public parks and recreation facilities have seen very little to no coverage in the literature. Several non-motorized transportation facilities with recreational purposes are located on low lying lands near shore lines in Delaware. This is a source of major problem in future in Delaware, which is a plain state, because many of these facilities are exposed to sea level rise and flooding caused by increased precipitation and storm surges. These facilities are going to be covered by water permanently or temporarily thus some questions arise: what is the level of exposure of each facility? are they going to be damaged? If so, how much will they be damaged?

Uncertainty around climate change and lack of knowledge and analysis regarding its impacts on non-motorized transportation will cause major problems in near future especially in plain areas like Delaware.

1.3 Objectives

This study is trying to assess the vulnerability of non-motorized transportation facilities against sea level rise in the State of Delaware. The objectives of the research can be summarized as follow:

- Assessing the number of trails that are going to be affected due to three scenarios of sea level rise.

- Assessing the length of trails that will be inundated due to three scenarios of sea level rise.
- Determining the level of service for affected trails based on vulnerability assessment
- Assessing the number of bike routes in Delaware that will be affected under three scenarios of sea level rise.
- Assessing the length of bike routes in Delaware that will be inundated under three scenarios of sea level rise.
- Determining the level of service for affected bike routes based on vulnerability assessment

The ultimate results that are expected to gain from this study are divided into three different sections. First, vulnerable trails and bike routes against sea level rise in 2100 are identified. The distance of the facilities that will be covered by water and the maximum depth of water on affected facilities are estimated by GIS-based analysis. In the third step, the vulnerability of facilities is estimated and reported as the level of service of that facility under different sea level rise scenarios.

1.4 Overview of Approach

As was mentioned in the previous section, this study includes three different parts. First, maps consisting of the location of non-motorized transportation facilities (trails and bike routes) were obtained and used to determine how much of these facilities will to be affected by sea level rise either completely or partially. It is worthwhile mentioning that three scenarios of sea level rise developed by the Delaware Department of Natural Resources and Environmental Control (DNREC) was used in this research. Based on these scenarios Delaware will experience either 2 feet, 4 feet, or 6 feet rise in sea level. The GIS-based data of sea level rise was obtained from the National Oceanic and Atmospheric Administration (NOAA). For each of the affected facilities based on the length of inundation and maximum depth of water, a vulnerability assessment is performed to demonstrate the risk which the facility will be confronted with by 2100. This risk is presented by the level of service that each facility will have under three sea level rise scenarios.

1.5 Scope

The science of climate change is both dynamic and complex thus there are a variety of climate change derivatives and indicators that will be addressed and covered in this research. These derivatives include frost days, cooling degree days, maximum 5-day rainfall, etc. The thesis concentrates on one climate change vectors; sea level rise. Flooding caused by storm surges and intense precipitation; and increased temperature and heat waves are the two most destructive consequences of climate change that their effect on non-motorized transportation should be studied in further researches.

There are several different types of non-motorized facilities, even shoulders of the road with widths more than 4 feet can be counted as biking facilities. However, in this study our focus is on two types of facilities; trails and bike routes.

As was mentioned earlier, the science of climate change is complex. Climate change derivatives for different geographic locations differ from each other. For example, in California heat waves are more important than freezing days which is reversed in northern States. Therefore, this research address climate change vectors that are more important in the mid-Atlantic region especially Delaware. Since Delaware is a flat state with a long coast line, sea level rise and flooding will become hazardous.

1.6 Implications and Outcomes

Although there is a great deal of uncertainty associated with climate change and weather projection, based on current observations and researches, climate change impacts are obvious all around the world. The major expected benefits and impacts of this project will be how planners and engineers can protect us and future generations from the negative impacts that climate change in particular sea level rise will have on our non-motorized transportation facilities. Transportation agencies and Department of Transportation (DOT) can use the methodology of this research to assess the vulnerability of non-motorized transportation facilities against climate change derivatives especially in the Mid-Atlantic region.

Government transportation agencies at different levels such as Delaware Department of Transportation (DelDOT) can use the results from this study both now and for their future non-motorized facilities planning. Since exact locations of affected facilities are indicated in the results section of the study, they can use the results of this work as a foundation for future adaptation planning and decision. Different adaptation strategies for different facilities can be selected by the management of the facility. For instance, elevating some parts of a trail that will be inundated or moving the trail land-ward to prevent frequent flooding. In addition, DelDOT can apply the results from this research for their future non-motorized transportation facilities planning. They can build new trails and shared use paths in locations that will not be affected in a hundred years. Thus, they can invest in non-motorized facilities in a smart way. Another significant outcome of this research is that management authorities of trails and bike routes can stop investing on maintenance of highly vulnerable facilities and spend the budget on building new facilities and retrofitting less vulnerable ones.

1.7 Organization of the Report

This report includes six chapters.

Chapter one- is an introduction to the research explaining what motivated this group to initiate doing research on this topic. This chapter also includes the questions that this work is trying to answer under the title of problem statement, the objectives of the research, the overview of approach, the scope of the study and finally implications and outcomes.

Chapter two- describes a brief background on climate change. This section includes a brief overview of climate change, how climate change affects human health.

Chapter three- describes the impacts of climate change on different modes of transportation including surface, air, and non-motorized transportation.

Chapter four- explains the methods of analysis that is used. This includes the sources of data, GIS-based analysis, and vulnerability assessment.

Chapter five- presents the results of analysis. The results include the level of service for trails and bike routes, and maps presenting the condition of Delaware's non-motorized facilities under three different scenarios.

Chapter six- summarizes conclusions, and recommendations. In addition, future research that could complete studying the effects of climate change on non-motorized transportation is explained.

Chapter 2

BACKGROUND ON CLIMATE CHANGE

2.1 Overview of Climate Change

The term climate is defined by very long-term processes over many years to decades, whereas the term weather deals with day to day weather variations that we experience. Despite, the fact that climate is simply a long-term average of many weather events, it is often the impact of the latter (e.g., Hurricane Katrina in 2005, Super storm Sandy in 2012, California drought of 2013–2014) that is more vividly remembered (Marchi, 2015). In the past, few decades, the term global warming was used frequently to address changes in climatic pattern however global warming is one of the several outcomes of the climate change. Although other features of climate are changing, they usually have been neglected in the literature reviews of this field.

Global warming describes as an average increase in temperatures near the earth's surface and in the lowest layer of the atmosphere. Increases in temperature in the atmosphere contribute to changes in global climate patterns. In addition to global, other significant outcomes of climate change are changes in precipitation, sea level rise etc. (Division of Energy and Climate, DNREC, 2014).

Climate change is described as any significant change in the measures of climate persisting for an extended time span (decades or longer). Many climate models project that future climate are likely to increase beyond the range of variability experienced in the past. Historical data and trends may no longer be reliable indicators for future climate conditions (US EPA, 2012).

2.1.1 Anthropogenic Activities and Climate Change

Humans are changing the composition of the atmosphere by adding carbon dioxide and visible particulates, called aerosols, mainly by burning fossil fuels. Other activities add methane and nitrous oxide, which along with carbon dioxide are greenhouse gases, so that they trap outgoing infrared radiation and warm the planet. In addition to changing the atmospheric concentrations of gases and aerosols, humans are affecting both the energy and water budget of the planet by changing the land surface, including redistributing the balance between latent and sensible heat fluxes. Land use changes, such as the conversion of forests to cultivated land, change the characteristics of vegetation, including its color, seasonal growth and carbon content (Foley et al., 2005;Houghton, 2003). For example, clearing and burning a forest to prepare agricultural land reduces carbon storage in the vegetation, adds CO_2 to the atmosphere, and changes the reflectivity of the land (surface albedo), rates of evapotranspiration and longwave emissions (Stocker, 2014). From 1990 to 2013, the total warming effect from greenhouse gases added by humans to the Earth's atmosphere increased by 34 percent. The warming effect associated with carbon dioxide alone increased by 27 percent (United States Environmental Protection Agency, 2014).

Greenhouse gases are defined as any of various gaseous compounds that absorb infrared radiation, trap heat in the atmosphere, and contribute to the greenhouse gas effect (Knutti, 2010). These include: CO_2, methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)). Greenhouse gases can remain in the atmosphere for varying lengths of time, from a few years to thousands of years. Consequently, the concentration of greenhouse gases increases over time. Water vapor is also considered a greenhouse gas in that it contributes to the warming of the earth, primarily because of the feedbacks related to increasing temperatures (Division of Energy and Climate, DNREC, 2014). There are several different sources contributing in emission of greenhouse gases. For example, in the United States electricity generation is the largest source of greenhouse gas emissions, followed by transportation. Greenhouse gas emissions caused by human activities increased by 5 percent from 1990 to 2012. However, since 2005, total U.S. greenhouse gas emissions have decreased by 10 percent (United States Environmental Protection Agency, 2014).

2.1.2 Greenhouse Gases

As energy from the sun reaches the earth, it warms the land and ocean surface. As the earth's surface warms, it radiates some of this energy back toward outer space as terrestrial or longwave radiation. Greenhouse gases in the atmosphere absorb some of that outgoing terrestrial radiation, and re-radiate it back toward the earth's surface, creating a "greenhouse effect" (Division of Energy and Climate, DNREC, 2014). Albedo (reflectivity) effect is a positive feedback that can cause less radiation absorbed by the earth surface. Ice and snow have a higher albedo or reflectivity than vegetation, soil, or water. As more of the land surface is covered by ice or snow, more solar radiation is reflected to space, less is absorbed by the surface, and temperatures decrease. Cooler temperatures lead to more ice growth, more reflection of solar radiation back to space, and even cooler temperatures (Division of Energy and Climate, DNREC, 2014). In addition, some aerosols increase atmospheric reflectivity, whereas others (e.g., particulate black carbon) are strong absorbers. Indirectly, aerosols also affect cloud albedo, because many aerosols serve as cloud condensation nuclei or ice nuclei. This means that changes in aerosol types and distribution can result in small but important changes in cloud albedo and lifetime. Clouds play a critical role in climate because they not only can increase albedo, thereby cooling the planet, but also because of their warming effects through infrared radiative transfer. Whether the net radiative effect of a cloud is one of cooling or of warming depends on its physical properties (level of occurrence, vertical extent, water path and effective cloud particle size) as well as on the nature of the cloud condensation nuclei population (Stocker, 2014).

2.1.3 Climate Change Stressors

There are many indicators of climate change. These include physical responses such as changes in the following: surface temperature, atmospheric water vapor, precipitation, severe events, glaciers, ocean and land ice, and sea level (Stocker, 2014). In addition, there are several climate stressors caused by climate change such as sea level rise, flooding, increased temperature etc. The key point is that a single climate stressor can result in a range of impacts. It is also important to note that the same type of change (e.g., warming air temperatures) can cause seemingly opposite effects depending on local topography, the season, urbanization, and other factors. Consider the case of winter precipitation in a region that typically experiences snowy winters. On the positive side, warmer winters throughout the United States may translate into less need for snow and ice removal for many airports. Conversely, in some locations, warmer temperatures may result in an increase in ice events (as snow events are replaced by rain, freezing rain, and sleet), presenting more severe adverse impacts in some locations. It is important to understand the range of impacts that changing climate may cause (Marchi, 2015).

Three of the most important climate change stressors are thoroughly described in this chapter.

2.1.3.1 Sea Level Rise and Flooding

Sea level rise and the associated increase in frequency and intensity of storm surges and flooding incidences are perhaps among the most worrying consequences of climate change, especially for coastal areas (Koetse and Rietveld, 2009).

Ocean levels have always fluctuated with changes in global temperatures. During the ice ages when the earth was 9°F (5°C) colder than today, much of the ocean's water was frozen in glaciers and sea level often was more than 300 feet (100 meters) below the present level (Kennett, 1982;Oldale, 1985). Conversely, during the last interglacial period (100,000 years ago) when the average temperature was about 2°F (1°C) warmer than today, sea level was approximately 20 feet higher than the current sea level (Mercer, 1968).

Many studies suggest that during the last century, worldwide sea level has risen 4 to 6 inches (10 to 15 centimeters) (Barnett, 1984;Fairbridge and Krebs, 1962). Much of this rise has been attributed to the global warming that has occurred during the last century (Gornitz et al., 1982;Meier, 1984).

Hughes and Bentley (1983) estimated that a complete disintegration of West Antarctica in response to global warming would require 200 to 500-year period, and that such a disintegration would raise sea level 20 feet (Smith, 1990).

Global warming from the greenhouse effect could raise sea level approximately 1 meter by thermal expansion of the upper ocean layers, melting mountain glaciers, and causing ice sheets in Greenland to melt or slide into the oceans. The frozen parts of the planet, known collectively as the cryosphere, are affected by, local changes in temperature. The amount of ice contained in glaciers globally has been declining every year for more than 20 years, and the lost mass contributes, in part, to the observed rise in sea level. Snow cover is sensitive to changes in temperature, particularly during the spring, when snow starts to melt. Spring snow cover has shrunk across the northern hemisphere since the 1950s. Substantial losses in Arctic sea ice have been observed since satellite records began, particularly at the time of the minimum extent, which occurs in September at the end of the annual melt season. By contrast, the increase in Antarctic sea ice has been smaller (Stocker, 2014). Climate change could also affect local sea level by changing ocean currents, winds, and atmospheric pressure; no one has estimated these impacts (Smith, 1990). Human modification of the hydrologic cycle could also affect sea level rise. Sequestration of water on land in reservoirs and through irrigation losses could exceed amounts transferred seaward by groundwater mining and increased runoff due to urbanization and deforestation (Vivien Gornitz, 2000). Although most studies have focused on the impact of global warming on global sea level, the greenhouse effect would not necessarily raise sea level by the same amount everywhere. Removal of water from the world's ice sheets would move the earth's center of gravity away from Greenland and Antarctica and would thus redistribute the oceans' water toward the new center of gravity (Smith, 1990).

The range of future sea level is uncertain as result of the varying projections of temperature increase, rate of thermal expansion, and anticipated melting of land-bound ice. Because of these series of uncertainties, scenario analysis is frequently used for assessing future sea level conditions (Marchi, 2015). In majority of the climate and sea level rise projections there are two or more scenarios which represent high, medium or low prediction. The lower scenarios represent a future in which people shift to clean energy sources in the coming decades, reducing emissions of carbon dioxide (CO_2) and other greenhouse (heat-trapping) gases that are causing climate to change so quickly. The higher scenarios represent a future in which people continue to depend heavily on fossil fuels, and emissions of greenhouse gases continue to grow (Division of Energy and Climate, DNREC, 2014).

The land slope especially along coasts are one factors that affects the amount of rising sea level in different regions. The visible part of the beach is much steeper than the underwater portion, which comprises most of the active "surf zone". While inundation alone is determined by the slope of the land just above the water, Bruun (1962) and others have shown that the total shoreline retreat from a sea level rise depends on the average slope of the entire beach profile. For instance, one meter rise could drown approximately 25 to 80% of the U.S. coastal wetlands. Coastal wetlands' ability to survive would depend largely on whether they could migrate inland or whether levees and bulkheads blocked their migration. This amount of rise could inundate 5,000 to 10,000 square miles of dryland if shores were not protected and 4,000 to 9,000 square miles of dryland if only developed areas were protected. A rise in sea level would enable saltwater to penetrate farther inland and upstream into rivers, bays, wetlands, and aquifers. Salinity increases would be harmful to some aquatic plants and animals, and would threaten human uses of water (Smith, 1990).

Sea level rise has direct and indirect effects in coastal regions. Extreme weather events are a key driver of these impacts. For example, coastal storms that produce high waves and storm surge cause significant damage when they occur during high tides. Rising sea levels amplify high tides, resulting in greater frequency, duration, and extent of coastal flooding. Even relatively small increases in sea level over the past several decades have contributed to higher storm surge and wind waves (Dettinger et al., 2004). With respect to North America the Intergovernmental Panel on Climate Change (2007a) report states that coastal flooding due to sea level rise and storm surge is one of the most serious effects of climate change, especially along the Gulf and Atlantic coasts (Fields et al., 2007). Some studies even predict that transport infrastructure in some coastal areas along the Gulf of Mexico and the Atlantic will be permanently inundated sometime in the next century (Dingerson, 2005).

Four reasons can be addressed as the causes of flooding due to sea level rise in coastal regions: (1) A higher sea level provides a higher base for storm surges to build upon. A 1-meter sea level rise would enable a 15-year storm to flood many areas that today are flooded only by a 100-year storm (Kana et al., 1984;Leatherman, 1984). (2) Beach erosion also would leave oceanfront properties more vulnerable to storm waves. (3) Higher water levels would reduce coastal drainage and thus would increase flooding attributable to rainstorms. In artificially drained areas such as New Orleans, the increased need for pumping could exceed current capacities. (4) Finally, a rise in sea level would raise water tables and would flood basements, and in cases where the groundwater is just below the surface, perhaps raise it above the surface.

Evidences show that sea level rise, storm surges and flooding incidences will become increasingly relevant for various coastal regions around the globe. Studies that analyze the impact of sea level rise on the transport system generally (if not all) analyze the land elevation data by Geographical Information Systems (GIS) to show the effects are likely substantial. For example, many elements of the transportation system in the US Metropolitan East Coast region lie at 6 to 20 feet above the current sea level, which is well within the range of future storm surge predictions assuming a global sea level rise of 3 feet (Jacob et al., 2007). More recently, Jacob et al. (2007) estimated that a meter global sea level rise would increase the frequency of coastal storm surges and flooding incidences by a factor 2 to 10, with an average of 3. They show that especially the lowest critical elevations of important infrastructure elements in the New York metropolitan area are at-risk of being flooded more often and more intensely (Koetse and Rietveld, 2009).

2.1.3.2 Intense Precipitation and Droughts

An extreme weather event such as tornadoes, severe thunderstorms, hurricanes, derechos, droughts, extreme heat waves, coastal flooding, storm surge, and extreme snowfall and rainfall (Marchi, 2015), is one that is rare at a particular place and/or time of year. Definitions of ‘rare’ vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. When a pattern of extreme weather persists for some time, such as a season, it may be classified as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season) (Stocker, 2014). For some climate extremes, such as drought, floods and heat waves, several factors such as duration and intensity need to be combined to produce an extreme event (Seneviratne et al., 2012).

Climate records show that changes are already being observed in the amount, intensity, frequency, and type of precipitation (Division of Energy and Climate, DNREC, 2014). Hydrological extreme events are typically defined as floods and droughts. As global temperatures increase, the warming climate is expected to increase precipitation in many areas, due to increased evaporation and cloud formation. Floods are associated with extremes in rainfall (from tropical storms, thunderstorms, orographic rainfall, widespread extra-tropical cyclones, etc.), while drought is associated with a lack of precipitation and often extreme high temperatures that contribute to drying (Trenberth and Shea, 2005). Overall, changes in patterns of drought and flooding are complex. In some regions, the extremes of wet and dry climate have a greater impact than changes in average precipitation. Heavy rain events have increased in many areas, even where average or total amounts of precipitation have decreased. The amount of rain falling in the heaviest rain events has increased by roughly 20 percent over the past century; this trend is expected to continue, with the greatest increases in the wettest areas (Vrac et al., 2007).

There is a direct influence of global warming on changes in precipitation and heavy rains. Increased heating leads to greater evaporation and thus surface drying, thereby increasing intensity and duration of drought. However, the water-holding capacity of air increases by about 7% per 1 ◦C warming, which leads to increased water vapor in the atmosphere, and this probably provides the biggest influence on precipitation (Trenberth and Shea, 2005). The distribution and timing of floods and droughts are most profoundly affected by the cycle of El Ni˜no events, particularly in the tropics and over much of the mid-latitudes of Pacific countries (Diaz and Markgraf, 2000). For instance, opposite phases of El Niño/Southern Oscillation (the interaction between the atmosphere and ocean in the tropical Pacific that results in a somewhat periodic variation between below-normal and above-normal sea surface temperatures and dry and wet conditions over the course of a few years) were shown by Trenberth and Guillemot to play a role in the 1988 drought and 1993 floods in North America. They showed that both the 1988 drought and 1993 floods developed as the result of a change in the large scale atmospheric circulation in the Pacific and across North America that altered the storm tracks into North America.

Precipitation has generally increased at high northern latitudes north of about 40 ◦N over the twentieth century and decreased since about 1950 in the tropics and subtropics, and especially from 10 ◦S to 30◦N (see Figure 2.1; (Jones et al., 2007)). In particular, it has become significantly wetter in the eastern parts of North and South America, northern Europe, and northern and central Asia, in part, because higher temperatures increase water-holding capacity and more precipitation falls as rain instead of snow (Trenberth and Shea, 2005), but drier in the Sahel (the arid area on the south wing of the Sahara desert that stretches across six countries from Senegal to Chad), the Mediterranean, southern Africa, and parts of southern Asia. In the more northern regions, more precipitation falls as rain rather than snow (Knowles et al., 2007; Mote, 2003). The liquid precipitation season has become longer by up to three weeks in some regions of the boreal high latitudes over the last 50 years (Jones et al., 2007) owing, in particular to an earlier onset of spring. In summary, the patterns of precipitation change have developed a distinctive pattern whereby higher latitudes have become wetter and the subtropics and much of the tropics have become drier (Trenberth and Shea, 2005).

An analysis of the future climate simulations by the latest generation of coupled climate models (Sun et al., 2007) shows that globally for each 1 ◦C of surface warming, atmospheric precipitable water increases by ∼9% and daily precipitation intensity increases by ∼2%, whereas daily precipitation frequency decreases by 0.7%. However, for very heavy precipitation which can be defined as more than 50mm per day, the percentage increase in frequency is much larger than in intensity (31.2% vs.

2.4%) so that there is a shift toward increased heavy precipitation. As temperature rises, the likelihood of precipitation falling as rain rather than snow increases, especially in autumn and spring at the beginning and end of the snow season, and in areas where temperatures are near freezing. Such changes are already observed in many places, especially over land, in middle and high latitudes of the Northern Hemisphere, leading to increased rains but reduced snow, and consequently diminished water resources in summer, when they are most needed (Knowles et al., 2007;Mote, 2003).

2.1.3.3 Temperature Change

Concentrations of heat-trapping greenhouse gases are increasing in the Earth's atmosphere. In response, average temperatures at the Earth's surface are rising and are expected to continue rising. However, because climate change can shift the wind patterns and ocean currents that drive the world's climate system, some areas are warming more than others, and some have experienced cooling (United States Environmental Protection Agency, 2014).

Based on one study, carbon dioxide concentration increased from 190 (ppm) in 800,000 BC to around 310 (ppm) in 1950. However, CO2 concentration increased by almost 90 (ppm) between 1950 and 2013 which shows a drastic change during this short time span (Lins, 2012). This proves that in recent decades the production of carbon dioxide has increased rapidly due to various reasons such as uncontrolled industrial activities.

The increases in surface air temperature and surface absolute humidity result in even larger increases in the heat index (a measure of the combined effects of temperature and moisture). The increases in surface air temperature also results in an increase in the annual cooling degree days and a decrease in heating degree days (Cubasch et al., 2001). It is important to note that warming has not been globally uniform. The recent warming has been greatest between 40°N and 70°N latitude, though some areas such as the North Atlantic Ocean have cooled in recent decades (IPCC Forth Assessment Report, 2007).

2.1.3.4 El Niño and ENSO

El Niño and the Southern Oscillation, also known as ENSO is a periodic fluctuation in sea surface temperature (El Niño) and the air pressure of the overlying atmosphere (Southern Oscillation) across the equatorial Pacific Ocean.

The Southern Oscillation describes a bimodal variation in sea level barometric pressure between observation stations at Darwin, Australia and Tahiti. It is quantified in the Southern Oscillation Index (SOI), which is a standardized difference between the two barometric pressures. Normally, lower pressure over Darwin and higher pressure over Tahiti encourage a circulation of air from east to west, drawing warm surface water westward and bringing precipitation to Australia and the western Pacific. When the pressure difference weakens, which is strongly coincidental with El Niño conditions, parts of the western Pacific, such as Australia experience severe drought, while across the ocean, heavy precipitation can bring flooding to the west coast of equatorial South America.

Although the exact initiating causes of an ENSO warm or cool event are not fully understood, the two components of it, sea surface temperature and atmospheric pressure, are strongly related. During an El Niño event, the easterly trade winds converging across the equatorial Pacific weaken. This in turn slows the ocean current that draws surface water away from the western coast of South America and reduces the upwelling of cold, nutrient–rich water from the deeper ocean, flattening out the thermocline and allowing warm surface water to build in the eastern part of the basin.

The strengthening and weakening of the trade winds is a function of changes in the pressure gradient of the atmosphere over the tropical Pacific. Ironically, the warming of the sea surface works to decrease the atmospheric pressure above it by transferring more heat to the atmosphere and making it more buoyant. So, in summary, the pressure gradient affects the sea surface temperatures, and the sea surface temperatures affect the pressure gradient.

The connection between the Southern Oscillation and precipitation is also manifest in the quantity of long–wave (e.g., infrared) radiation leaving the atmosphere. Under clear skies, a great deal of the long–wave radiation released into the atmosphere from the surface can escape into space. Under cloudy skies, some of this radiation is prevented from escaping. Satellites can measure the amount of long–wave radiation reaching space, and from these observations, the relative amount of convection in different parts of the basin can be estimated.

In addition, the thermal expansion of the warming water in the eastern part of the basin measurably raises sea level in these regions, and this change in sea level can be measured by satellite sensors. Therefore, variations in sea level are good indicators of the presence of an El Niño. During an El Niño, sea level in the eastern Pacific is well above average, while during a La Niña, the increased flow of cold deep water to the surface acts to lower the sea level.

2.2 Climate Change Impacts on Human Health

Recognition that climate change can affect human health in numerous ways is a recent development that represents the depth of scientific knowledge. Since centuries ago climatic disasters distort communities and populations causing famine, infectious diseases, floods, social collapse and disappearance of whole populations, etc. In some case, it causes new health threats and in other cases it exacerbates existing health threats. Age, economic resources and location indicate the level of risk for different people. Climate change is also likely to affect biodiversity and the ecosystem goods and services that we rely on for human health. Direct impacts of climate change are exposure to weather extremes such as heatwaves and winter cold, increase in extreme weather events like floods, cyclones, storm surge and drought, increased air pollution and production of aeroallergens. Indirect impacts include economic and political disruption such as effect on regional food yields and water resources. Modeling of climate change demonstrates that there will be an increase of 5-10% in future underfed people (McMichael et al., 2006). In the longer term and with considerable variation between populations as a function of geography and vulnerability, these indirect impacts are likely to have greater magnitude than the more direct (Campbell-Lendrum et al., 2003).

2.2.1 Temperature Rise

The IPCC, intergovernmental panel for climate change, estimates about two degree Celsius rise in global average warming by the end of the century (Patz and Hatch, 2014). The unusually rapid temperature rise since the mid-1970s is substantially attributable to this anthropogenic increase in greenhouse gases) (McMichael et al., 2006). There are numerous adverse climate events associated with increase in temperature. High temperature expedites evaporation of moisture from soil causing droughts. On the other hand, warm air preserves humidity resulting in intense precipitation and flooding (Patz and Hatch, 2014). Both rising temperature and increase in rainfall will decline the air quality of indoor areas by rising the probability of growing indoor fungi and molds which lead to increase in respiratory illnesses such asthma-related conditions (John Balbus, 2014).

2.2.2 Heat Wave

From 1999 through 2009, 7800 deaths are recorded in United States caused by exposure to extreme heat (White House, 2014). As temperature continues to rise due to climate change, heat waves are expected to become more frequent, intense and longer lasting in coming decades. Extreme heat increases cardiovascular, cerebrovascular, respiratory and kidney diseases and deaths from heat stroke and other related conditions. Recently, variability in climate change in future has been studied. Small changes in temperature variability, along with a shift in mean temperature can greatly increase the frequency of extreme heat (McMichael et al., 2006).

Urban and non-urban population act differently towards heat waves. People living in urban environment are at greater risk than those who live in non-urban regions. Two major factor cause this discrepancy, first inefficient housing and second, urban heat island effect. Inner urban environment, with high thermal mass and low ventilation, absorb and retain heat which results in higher temperature than surrounding sub-urban and rural areas.

2.2.3 Flood

Increase in both extreme precipitation and total precipitation result in increase of severe flooding events in certain regions. The most frequent natural weather disaster was flooding (43%), killing almost 100,000 people and affecting over 1·2 billion people (McMichael et al., 2006). In 2010, Flood has been reported the deadliest among other natural disasters by having 175 million victims. Immediate effects of flooding are physical injury, morbidity and mortality. In some cases, flooding may lead to mobilization of dangerous chemicals from storage or remobilization of chemicals already in the environment, e.g. pesticides. In addition to immediate health hazards associated with extreme precipitation events when flooding occurs, other hazards can often appear once a storm event has passed. Following flood, food-borne illnesses, diarrheal diseases, respiratory diseases and vector-borne disease transmitted by mosquitos and mice like Malaria, and Dengue fever have been reported. As a result of overflowing water excessive rainfall also facilitate entry of human swage, animal wastes and agricultural field pollution in to waterways and drinking water supplies, increasing the risk of water-borne diseases.

2.2.4 Drought

Droughts associated with climate change may lead to population displacement and more environmental refugees (Haines et al., 2006). Famine and malnutrition are the results of droughts and crop failure. Nelson (2009) found that by 2050 yields of staple crops would decline in developing countries and that child underweight would be approximately 20 percent higher, equivalent to approximately 25 million children being affected (Nelson et al., 2009). Long periods of high temperature are associated with occurrence of wildfires in some areas. Wildfires contain particulate matter, carbon monoxide, nitrogen oxides and volatile organic compounds that can significantly reduce air quality.

2.2.5 Aeroallergens

As frost-free days and air temperature increase due to climate change, the production of plant-based allergens would be greater. For example, in some communities in northern states the length of ragweed seasons has increased (White House, 2014). Experimental research has demonstrated that doubling CO2 levels from 300 to 600 ppm causes a four-fold increase in the production of ragweed pollen. Pollen-related allergies have been increased because of longer pollen season and greater pollen concentration. In addition, asthma episodes that lead to diminish productivity and loss of school days will increase.

2.3 Summary of the Chapter

Climate refers to weather patterns in a long period of time and climate change refers to any extreme changes in these patterns. Over past centuries especially last century, human activities have caused drastic changes in weather patterns by increasing atmosphere temperature. Anthropogenic activities like transportation produce cast amount of greenhouse gases (carbon dioxide, methane, nitrous oxide, fluorinated gases, perfluorocarbons, and sulfur hexafluoride) which eventually result in increased temperature.

Increased temperature has caused different climatic stressors such as sea level rise, more frequent flooding, intense precipitation, droughts, and heat waves. Different regions in the world are experience different climate change stressors for instance while in Mid-Atlantic region sea level rise in coastal areas is of a great importance, droughts and its consequences are noticeable. In this chapter of the thesis the climate change stressors are addressed and a comprehensive literature review is performed for each of the stressors.

In addition, how these climatic extremes will affect human health is discussed in this chapter. As it was mentioned earlier floods, droughts, and other climate change consequences have positive and negative influences on human life and health. This chapter explained these effects in details.