Quantifying the impacts of climate-driven flood risk changes and risk perception biases on coastal urban property values

-A case study for the North Carolina coastal zone-

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Title: *Quantifying the impacts of climate-driven flood risk changes and risk perception biases on coastal urban property values*

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Cover Photo: *ISS007-E-14883 provided by NASA: This close-up view of the eye of Hurricane Isabel was taken by one of the Expedition 7 crewmembers on board the International Space Station (ISS). "It is quite interesting to look at storms, said Ed Lu, Expedition 7 science officer. "When you see a large cyclone, you can see the spiral structure, and you can actually see – if there is a hurricane – you actually see the eye of the hurricane. You can look right down into it if you are lucky enough to go right over the top."*

Summary

Between 1991 and 2010, hurricanes and tropical storms were the biggest cause of property losses, causing 44% of all disaster related property destruction in the U.S. The projected growth in population of coastal counties, with the accompanying rise in coastal asset value, in combination with the impacts of the expected ongoing climate change poses an ever growing financial liability to the U.S. taxpayer and coastal resident. Since housing is a major source of collateral for the financial system, being able to simulate property values may help reveal the true risk of future climate change to financial institutions. However, the market value of these houses is influenced by the risk perception bias of buyers who operate in the market. This research focusses on these subjects affecting coastal urban property values and are reflected in the research objective:

> *"To quantify the impacts of climate change, and the effect of the associated flood risks and risk perception bias on coastal urban property values at the North Carolina coastal zone."*

First, the impacts of climate change on Beaufort (Carteret County, North Carolina, U.S.) for the year 2050 is downscaled from the global climate change scenarios. Carteret County is one of the counties most often hit by a hurricane and as it is situated on the coastal plain, regional sea level rise and changing hurricane frequencies will be the focus of the climate change impacts. The regional sea level rise for the year 2050 is less than 30 cm, this is too small to be used during this study and is therefore omitted. For Carteret County the dominant source of flooding are wind driven storm surges associated with hurricanes. Under climate change conditions the current 100 year storm will have a return period of 61 years by 2050 and the current 500 year storm will be more than twice as likely to occur in 2050 with a decreased return period of 231 years.

Second, divided into three subjects, risk will be explored by taking a look at objective risk, subjective risk, and the risk perception bias procedure. The objective risk is either the current flood risk probability, as determined by the Federal Emergency Management Agency, or the hurricane return period under climate change. Housing market actors will assess objective flood risk on the basis of probability and severity of damage, this is the subjective risk, and will be biased by myopia and amnesia. The risk perception bias procedure is started by a flood event, over a period of 5 years the bias declines logarithmically from its maximum to its minimum level.

Third, four scenarios were developed to help achieve the research objective. Scenario 1 and 2 both operate under objective risk and without and with climate change conditions respectively. Scenario 3 and 4 operate under subjective risk and without and with climate change conditions respectively. The four scenarios are monitored for four flood zones, for each of these flood zones the total trade volume, average trade price, and the number of trades are recorded. Whilst the number of trades remains constant across the different scenarios, the total trade volume and average trade price can be as much as 20 percent lower due to the impacts of climate change and risk perception bias.

Finally, recommendations are made for future research. The relation between hurricane intensity and storm surge levels for Carteret county as well as adding hurricane wind damage as a starting point for the risk perception bias should be the subject of future research.

Preface

In November 2014 I started with the final leg of my study Civil Engineering at the University of Twente. Today six months later, I am proud to present the findings of my research. The goal of this research has been to quantify the impacts of climate change and risk perception bias on coastal urban property values, however, this study has also provided me with the opportunity to improve my modelling and analytical skills and my academic writing.

I would like to thank my supervisors, Tatiana, Erik, and Suzanne, for all their help in bringing my thesis to a successful end and for all the times is was able to barge into your offices unannounced with yet another question.

Next I would like to thank my sister Eveline, who always told me I could do it even when I didn't think I could. To my girlfriend Sofieke, who kept me going during a very difficult year even when I thought the situation was hopeless.

A special thank you is reserved for my parents, Peter and Petra, without whom I never would have been able to spend all these wonderful years as a student in Enschede. Papa en mama, bedankt voor alles.

Johan de Waard

Enschede, May 2015

Contents

List of acronyms

ABM	Agent-based modeling
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
CMIP3	Coupled Model Intercomparison Project 3
ENSO	El Niño-Southern Oscillation
GHG	Green House Gases
GIA	Glacial Isostatic Adjustment
GMSL	Global Mean Sea Level
IPCC	Intergovernmental Panel on Climate Change
NAO	The North Atlantic Oscillation
NOAA	National Oceanic and Atmospheric Administration
PDO	Pacific Decadal Oscillation
RCP	Representative Concentration Pathways
RF	Radiative Forcing
RHEA	Risks and Hedonics in Empirical Agent-based land market model
RSL	Relative Sea level
SRES	Special Report on Emission Scenarios
TAR	Third Assessment Report
WGI	Working group 1
EU	Expected Utility
FEMA	Federal Emergency Management Agency

1. Introduction

In this first chapter the background for this research will be presented. The research objective and the research objectives that are addressed in this thesis will be introduced. The methodology and scope are discussed before ending the introduction with the research strategy and thesis outline presenting a guide to the coming chapters.

1.1. Background

Flooding is the most common natural disaster in the United States. Between 1991 and 2010, hurricanes and tropical storms were the biggest cause of property losses among all natural catastrophes, causing 44 percent of all disaster related property destruction in the U.S. (Polefka, 2013). With the global climate changing and its projection to continue changing over this century (Melillo, Richmond, & Yohe, 2014) coastal systems and low-lying areas will increasingly experience the adverse effects of climate change. As of 2010 39% of the U.S. population lives in counties with a coastline. Between the period of 1970-2010 these coastal shoreline counties have seen a large increase in population and are projected to grow even further (Crosset, Ache, Pacheco, & Haber, 2013). The projected growth in population of coastal counties, with the accompanying rise in coastal asset value, in combination with the impacts of the expected ongoing climate change poses an ever growing financial liability to the U.S. taxpayer and coastal resident.

Since housing is a major source of collateral for the financial system, being able to simulate property values may help reveal the true risk of future climate change to financial institutions. The worldwide economic crisis starting with the U.S. sub-prime mortgage crisis has revealed how vulnerable the world's financial system is to changes in property values. An important implication of growing flood risks is in the destabilizing effect that the resulting unanticipated house price declines can have (Pryce, Chen, & Galster, 2011).

It is important to keep in mind that the market value of houses vulnerable to flooding forms the basis of estimating direct flood damage in residential areas. However, the market value of these houses is influenced by the risk perception bias of buyers who operate in the market. A price discount effect exists which changes with time, this discount effect is connected with the risk perception bias of buyers, it grows after a disaster and vanishes shortly after. The dynamics of the risk perception bias requires an adaptive model such as the RHEA model. In this respect a purely hedonic model would not have been an option, since hedonics use a snapshot of the market in time. A statistical spatial model would be equally unsuitable as it wouldn't allow for changes in individual demand due to dynamic risk perceptions reflected in housing prices.

1.2. Research objective and research questions

This research focusses on two separate subjects affecting coastal urban property values: climate change and risk perception bias. The Risks and Hedonics in Empirical Agent-based land market (RHEA) model by Filatova (2014) will be used to tie the two subjects together. Using the RHEA model the objective of this research is:

"To quantify the impacts of climate change, and the effect of the associated flood risks and risk perception bias on coastal urban property values at the North Carolina coastal zone."

Using global and local climate change scenarios for the U.S. Atlantic coast, the influence of climate change on coastal zones will be determined for the main climate impacts: relative sea level rise and extreme sea level events (Field et al., 2014). The impacts of relative sea level rise and extreme sea level events on the coastal zone will be used to determine changing flood risks and perceived risks for coastal properties and its consequences for coastal property values. In order to help achieve the research objective, the following research questions have been formulated:

1. To what extent will future climate change affect flood risks of the North Carolina coastal zone?
    a. What climate change scenarios are expected for the North Carolina coastal zone?
    b. What are the effects of climate change on submergence for the North Carolina coastal zone?
    c. What are the effects of climate change on coastal flooding for the North Carolina coastal zone?
2. How can (changes to) future flood risks and risk perception bias be simulated for the North Carolina coastal zone under variable climate change scenarios?
    a. How are the effects of flood risks on property values to be simulated with the RHEA model?
    b. How is risk perception bias to be incorporated into the RHEA model?
3. What is the impact of coastal flood risk changes and risk perception bias on coastal property values at the North Carolina coastal zone?
    a. Which scenarios should be considered to determine the impact of coastal flood risk changes and risk perception bias on coastal property values at the North Carolina coastal zone?
    b. How is the total market value of coastal properties affected under the different scenarios?
    c. How is the average market value of coastal properties affected under the different scenarios?
    d. How is the number of trades of coastal properties affected under the different scenarios?

1.3. Methodology

This section describes the methodology used in this research, to allow the research objective to be achieved. The research questions show us that this research will comprise three parts: (i)climate change and the consequent flood risk changes; (ii) the modelling of future coastal property values when exposed to flood risk and the way to include risk perception in this modelling; and (iii) a study of the impacts of climate change and risk perception on future coastal property values.

To be able to properly execute the first part it is necessary to start with the latest global climate change scenarios. These will be downscaled from the global level to fit the scope of this study.

Downscaling the global climate change scenarios allows the relevant climate impacts to be identified as well as the magnitude of these climate impacts.

Part 2 starts by properly identifying the kinds of risk relevant to this research, to be able to properly assess the impacts of risk perception bias. Once identified were the risk perception bias comes from, how this functions, and how it should operate within the market a procedure can be written to incorporate it into the existing RHEA model.

The final part will combine climate change and risk perception bias in order to reach the research objective. In order to properly analyze the scenarios, the results will be indexed. The starting values of each scenario will be the base index and therefore receive the index value 100, this allows to quickly assess the results.

1.4. Scope

The research questions introduced above will be addressed through a case-study for the North-Carolina coast. The study area chosen for this study is narrowed down to the town of Beaufort located in Carteret County, North Carolina in the U.S. Beaufort has been used as study area before in a number of different studies e.g. (Bin, Kruse, & Landry, 2008; Bin, Poulter, Dumas, & Whitehead, 2011; Filatova & Bin, 2013; Filatova, 2014), this means that relevant data for Beaufort is available as well as a valid representation within the RHEA model. This chapter contains a brief description of the study area.

1.4.1. Beaufort, Carteret County, North Carolina

The study area is located on the eastern seaboard of the United States, in Beaufort, Carteret County, North Carolina (Figure 1). North Carolina's coastal plain covers almost half of North Carolina (Wikipedia, 2015), with 5000 km^2 of the land area below 1 m elevation this part of North Carolina is very vulnerable to sea level rise (Bin et al., 2011).

Carteret county (Figure 1b) is one of the counties most affected by hurricanes, 22 hurricane strikes have been reported to hit Carteret county between 1900 and 2010 (NOAA National Hurricane Center, 2014). On the eastern U.S. seaboard only three counties have had more hurricane hits. Two of these counties are located on the most southern tip of Florida and the third one is Dare county which is situated to the north-west of Carteret county.

The total area of Beaufort is 14.5 km^2 of which 12 km^2 consists of land (Figure 1c). During the 2010 census the population of Beaufort was set at 4039 residents (Wikipedia, 2015). The area in the GIS dataset used within the RHEA model contains 7106 parcels, of which 3588 are residential parcels. Half (50%) of the residential parcels are located in the zero flood occurrence zone, whereas 27% and 23% of the residential parcels are located within the 1:100 and 1:500 flood zones, respectively (Filatova, 2014).

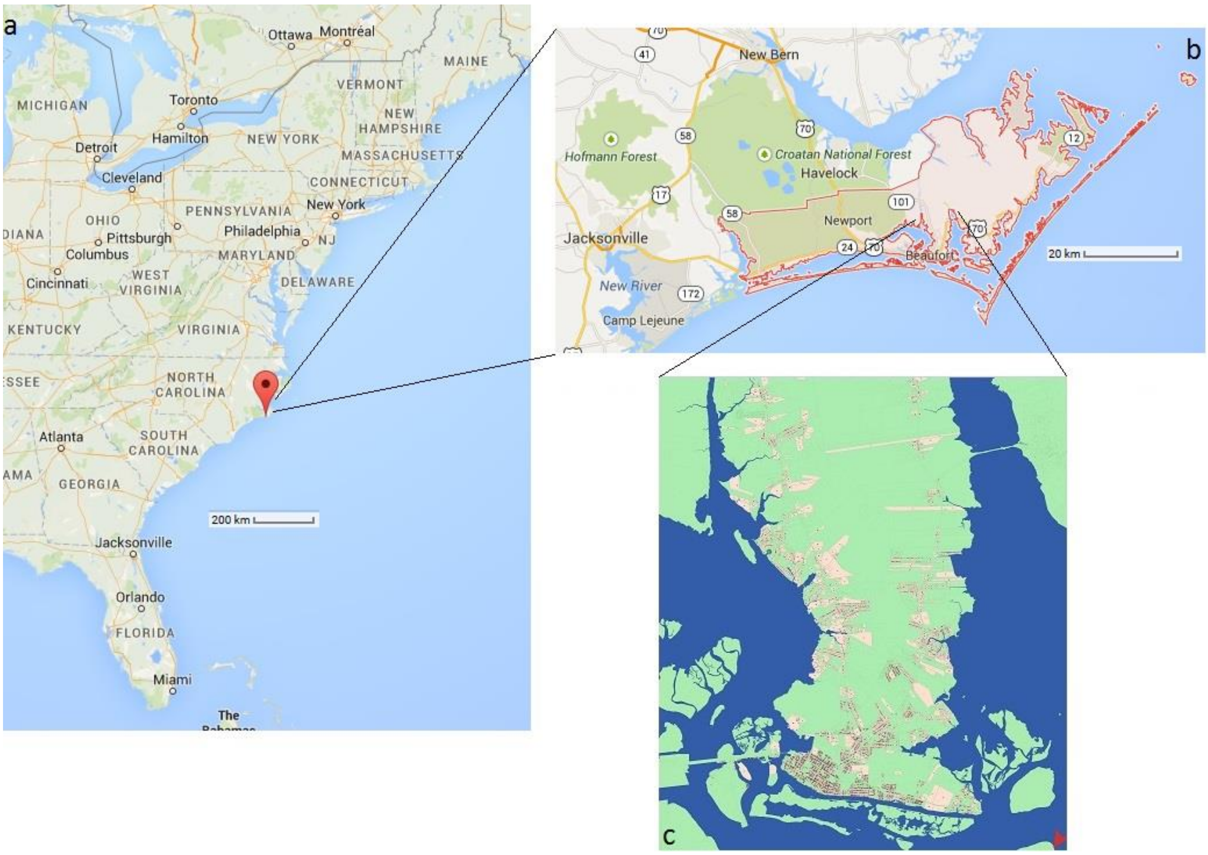

Figure 1: Location of Beaufort in the continental United States and overview of the study area (c). Top images (a and b) from (Google, 2015)**, bottom image from** (Filatova, 2014)**.**

1.4.2. Coastal characteristics

The town of Beaufort is not situated directly on the Atlantic coast, instead it is protected from the ocean by a chain of barrier islands. These barrier islands are common throughout North Carolina and are often inhabited. The barrier islands protect Beaufort from, among other things, erosion. Figure 2 shows whether the barrier islands are experiencing erosion or accretion. With large sections of the barrier islands eroding, the Carteret county shore protection office set up a beach preservation plan to counter the erosion and maintain the inhabited Atlantic Beach barrier islands protecting Beaufort and Morehead City (Carteret County Shore Protection Office, 2014). For the uninhabited Shackleford Banks no beach protection plans are in effect, as beach nourishment "would have significant potential to adversely impact the undisturbed ecosystem and recreational uses, including surfing, fishing, and shelling on Shackleford Banks" (Carteret County News-Times, 2014).

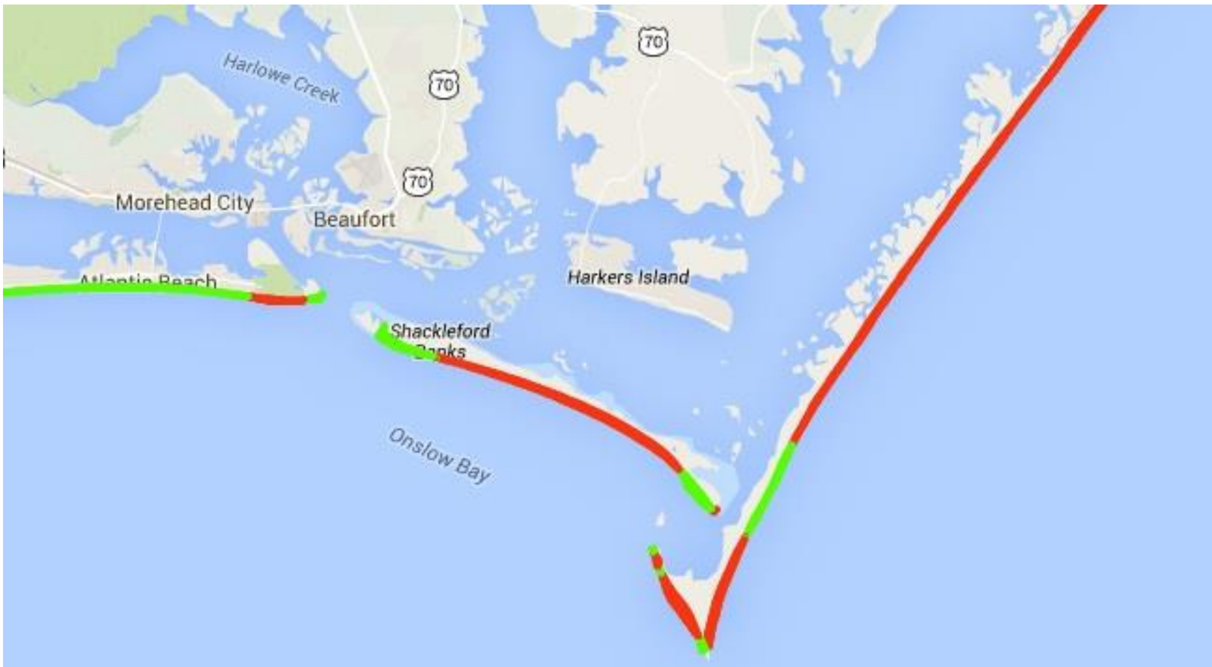

Figure 2: Erosion and accretion of the barrier islands visualized, red shows erosion and green shows accretion (N.C. Division of Coastal Management, 2014)**.**

1.5. Research strategy and thesis outline

To answer the research questions and to achieve the research objective put forward in the previous section, the strategy described below is used.

Chapter 1.4 introduced the scope. In this chapter we take a look at Beaufort, North Carolina, both geographically and demographically. By studying Beaufort we can determine which climate impacts (increasing flood damage, dry-land loss due to submergence and/or erosion(Field et al., 2014)) are relevant physical impacts of future climate change, as is put forward in the central research question.

Chapter 2 is devoted to the RHEA model. In this chapter we will take a look at agent based modeling in general, discuss the RHEA model, look into the input needed to run the model, and review the sensitivity of the RHEA model to its input parameters.

The objective behind research question 1a is to find the proper information on climate change scenarios to be used in this research. Chapter 3 aims to achieve this objective by making use of existing climate studies performed on both a global scale as well as a regional scale. The studies done by the Intergovernmental Panel on Climate Change and local subsidiaries will provide the relevant information on the expected global and local climate change.

Chapter 3 will also see research questions 1b and 1c answered. The objective for these two research questions is to quantify the physical impacts of climate change, which can later be used as input for the RHEA model. Research question 1b aims to determine the level of submergence to be expected under climate change conditions for Beaufort, North Carolina. Research question 1c addresses the frequency of coastal flooding.

The objective behind research question 2 is to define a way to simulate flood risk under climate change conditions as well as risk perception bias, both within the RHEA model. Chapter 4 seeks to achieve this objective and provides methods to quantify the levels of flood risk, both objective as well as subjective, for Beaufort and its residents.

The answers to the final research question will be able to form a bridge between climate change and risk perception bias in chapter 5. In response to research question 3a, this chapter will first define the scenarios to be used in the simulations with the RHEA model. The results from these simulations will be compared in order to obtain insights regarding research question 3b.

This research will be concluded with the discussion in chapter 6 and the conclusions and recommendations in chapter 7. In the final chapter the research objective will be achieved.

2. Model description

This chapter explores the model which lies at the basis of this research. First we take a look at agent-based models in general. Then the RHEA model is introduced, including the input required to run the model.

2.1. Agent-based models

Agent-based modeling (ABM), also known as individual-based modeling, is the modeling of phenomena as dynamical systems of interacting agents (Castiglione, 2006). In ABM, a system is modeled as a collection of autonomous decision-making entities called agents. Each agent individually assesses its situation and makes decisions based on a set of rules. This makes it possible to study the combined effect of individual decisions on a systems level (Bonabeau, 2002). ABM allows one to simulate the individual actions of diverse agents, measuring the resulting system behavior and outcomes over time (Crooks, Castle, & Batty, 2008).

Compared to other modelling techniques the benefits of ABM can be made in three statements: (i) ABM captures emergent phenomena; (ii) ABM provides a natural description of a system; (iii) ABM is flexible, it is easy to add more agents and it provides a natural framework for tuning the complexity of the agents (e.g. behaviour, degree of rationality, ability to learn and evolve and rules of interaction) (Bonabeau, 2002).

2.2. RHEA model

The Risks and Hedonics in Empirical Agent-based land market (RHEA) model was introduced by Filatova (2014). The RHEA model captures natural hazard risks and environmental amenities through hedonic analysis and allows for empirical agent-based land market modeling. In this section a description of the most relevant aspects of the model will be given. For additional information on the model, the reader is directed to the paper by Filatova (2014) on the RHEA model.

There are three types of agents represented in the RHEA model: (i) households, willing to buy and sell properties; (ii) real estate agents, who observe market dynamics and form expectations and; (iii) parcels, that can either be residential, which represents spatial goods, or non-residential. The three agents are connected to each other through the housing market, a visual representation can be found in Figure 3.

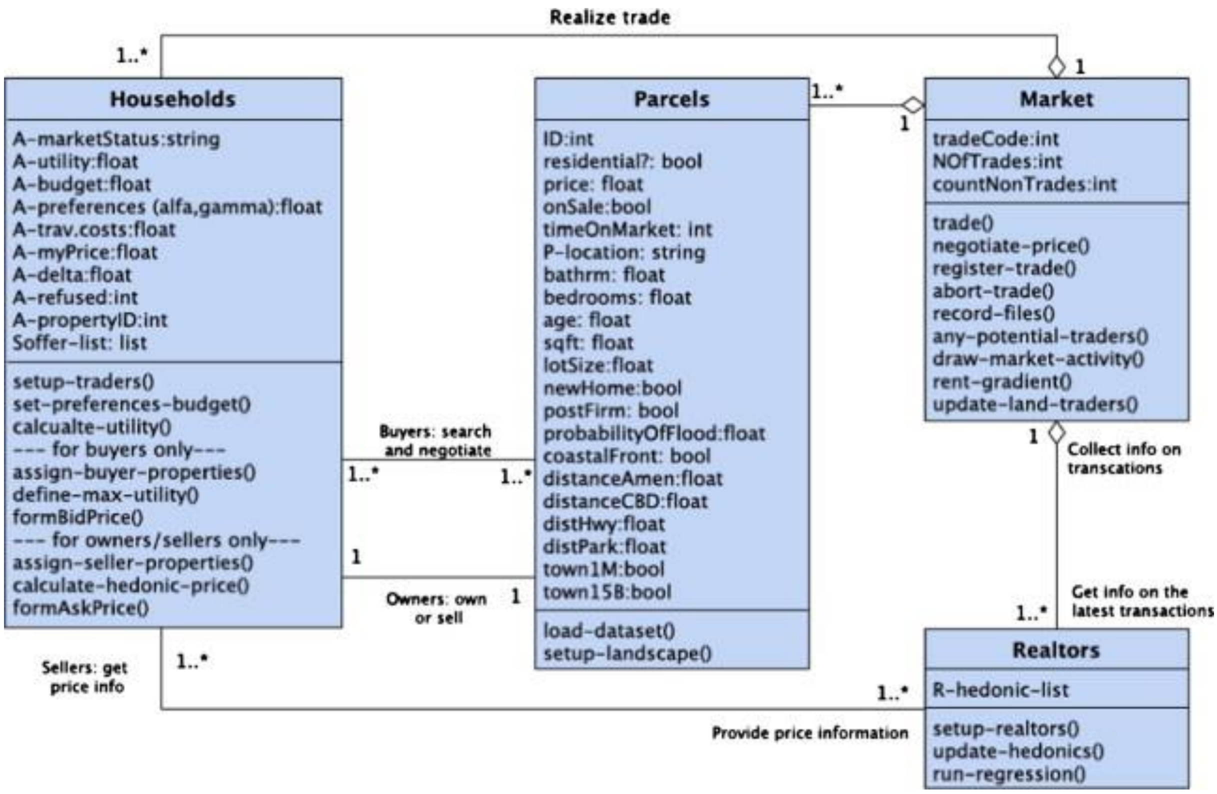

Figure 3: Unified Modeling Language class diagram of the housing market: agents, their properties and functions. (Filatova, 2014)

The trading of residential properties and the allocation of households in a town is the main process in the ABM. Each time step the trade process consists of several phases: listing of vacant spatial goods in a market by sellers; search for the best location under budget constraint by buyers; formation and submission of bids by buyers to sellers; evaluation of received bids by sellers; price negotiation, transaction and registration of trade; and finally updating of market expectations by realtors (real estate agents). The sequence of events in one time step is presented in Figure 4.

At the beginning of a trading period active sellers announce their asking prices. They do so by requesting regression coefficients from the hedonic analysis of the current period (box II, Figure 4) and applying them to their property (box III, Figure 4). As the model runs and new transactions occur, real estate agents are rerunning the hedonic analysis. Regression coefficients – i.e. willingness to pay for a specific attribute of a property of an average household in a current market – may change driven by the inflow of new households with different preferences for locations or potentially dynamic perceptions regarding flood risks. After buyers make their choices (boxes IV–VII, Figure 4), all sellers check how many bid-offers they received. They choose the highest bid to engage in price negotiations (box VIII, Figure 4). The transaction price is defined through a price negotiation procedure, which is based on bids and asking prices and relative market power of traders.

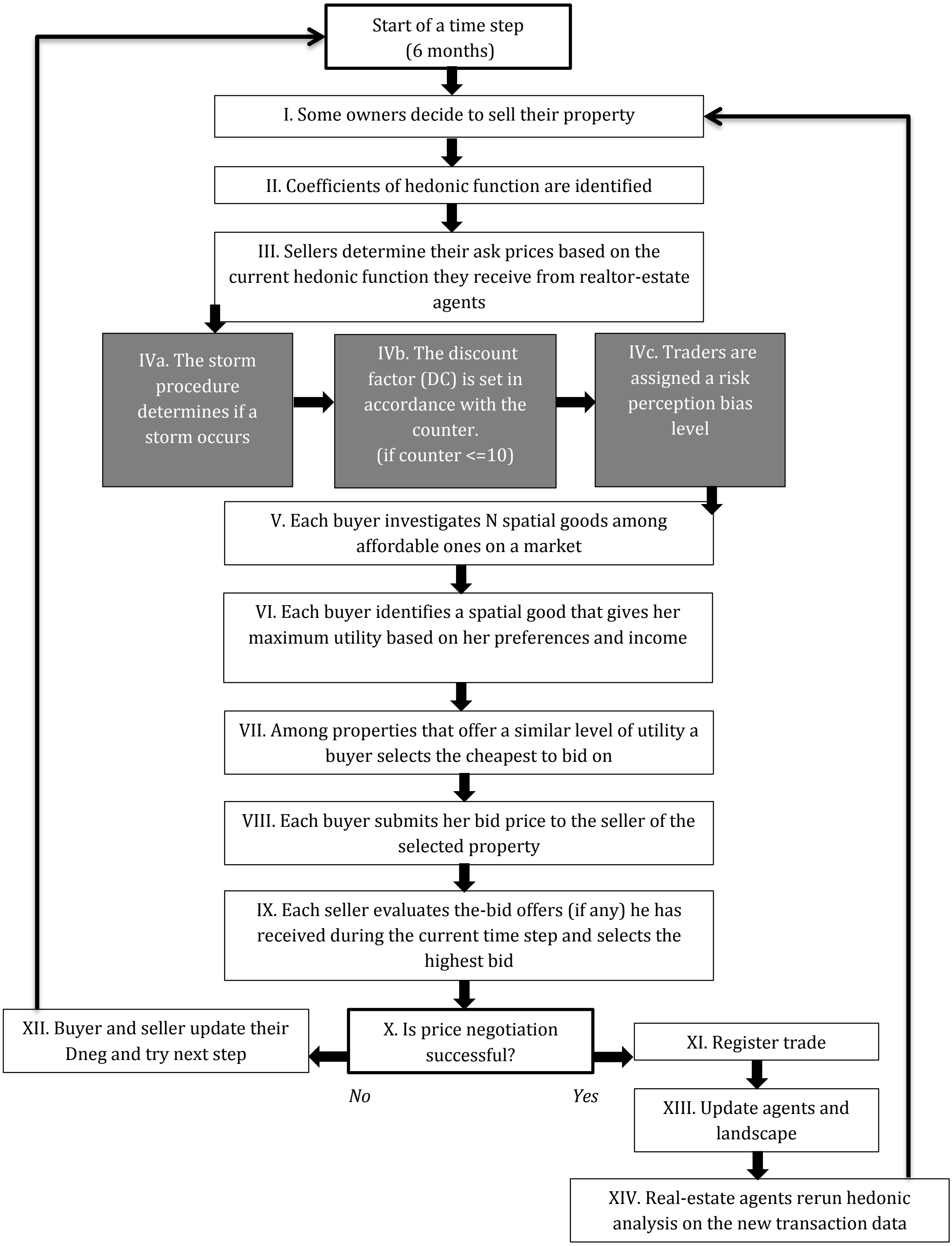

Figure 4: Dynamics of the trade process: a sequence of actions, which agents perform within 1 time step of the bilateral agent-based housing market with expectations formation (Updated from Filatova, 2014)**. Boxes IVa,b,c show the procedures which have been added during the course of this research, the NetLogo code for these procedures can be found in appendix D2.**

When choosing a location in a coastal town with designated flood zones, a household operates under the conditions of uncertainty due to the flood risk at the location of the property. Since a buyer searches for a property that will maximize its utility, the buyer will now aim to maximize its expected utility (EU). Utility is defined as the enjoyment or satisfaction people receive from consuming goods and services (Hubbard, Garnett, Lewis, & O'Brien, 2014). When a buyer is trying to maximize utility, he is looking for the property that will give him the most satisfaction considering his preferences and income.

$$EU = P_i U_F + (1 - P_i) U_{NF} \quad [1]$$

Wherein U_F is the utility in case of a flood, U_{NF} the utility in case of no flood and P_i is the subjective perception of risk the buyer has. Equations [2] and [3] show the respective formulas for U_F and U_{NF}:

$$U_F = s^{\alpha}(Y - T(D) - k_H H_{ask} - L - IP + IC)^{1-\alpha} A^{\gamma} \quad [2]$$

$$U_{NF} = s^{\alpha}(Y - T(D) - k_H H_{ask} - IP)^{1-\alpha} A^{\gamma} \quad [3]$$

Calculating the household's utility depends on housing goods (s) which are affordable for the buyer in their budget (Y) net of transport costs (T(D)). Preferences for housing goods and amenities are represented by α and γ, respectively. (L) represents the damage in case of a flood, (IP) the insurance premium and, (IC) the insurance coverage in case of a disaster. The buyers search for the property that provides the highest utility to them. Once a buyer has located the property that yields the highest utility, a bid price is offered to the seller (box VII, Figure 4) and price negotiations will start, Figure 33 in appendix C1 shows the price negotiation process (Filatova, 2014).

2.3. Model input

The RHEA model requires a number of different input parameters to be able to run. Spatial data is extracted from GIS data sets defining the locations of residential housing, coastal amenities, distances to the central business district, and others. Realtor-agents in the model use the empirical hedonic function developed by Bin et al. (2008), which is based on the real estate transactions from 2000 to 2004. To run the hedonic function, structural characteristics of the property, such as total square footage and the number of bathrooms, are required along with data on households incomes and preferences. Flood zones and the associated flood probability of 1:100 and 1:500 are represented as well. The remaining input parameters, their abbreviations and a short description of what they do can be found in Table 13 in appendix C2.

2.4. Changes in the RHEA model

In order to answer the research questions a number of changes need to be made to the model. New flooding probabilities and the possibility to change between current and future flooding probabilities needs to be introduced into the model. This change will give the model the proper functionality to determine the influence of climate change. The current risk perception bias of the RHEA model needs to be replaced with a dynamic risk perception bias procedure. Boxes IVa,b,c from Figure 4 show the procedures added to allow this to happen, the corresponding NetLogo code can be found in appendix D2. Lastly, a functionality needs to be added to allow for the proper variables to be monitored to be able to answer the research questions. Currently the RHEA model monitors variables related to the entire population of properties, instead of the properties being traded during a time step which are required for this research, these can also be found in appendix D2.

3. Climate change and its impacts

In this chapter we will discuss climate change and the relevant impacts climate change have on the study area. We start by examining the latest climate change scenarios developed by the Intergovernmental Panel on Climate Change. Both the global mean temperature change and the Eastern North American mean temperature change are discussed. The regional climate change models examine the Eastern North American mean temperature change.

In chapter 1.4 we learned that Carteret County is one of the counties most often hit by a hurricane and as it is situated on the coastal plain, sea level rise is a serious threat as well. Beaufort however, is not affected by erosion as the barrier islands protect it. This chapter will conclude with investigating how local sea level rise and hurricane frequencies change under climate change scenarios.

3.1. Global climate change

Late September 2013 the results from Working Group I (WGI) of the Intergovernmental Panel on Climate Change for the Fifth Assessment Report (AR5) were released. One of the most notable changes in the AR5 are the scenarios for future emissions of greenhouse gases. The Fourth Assessment report (AR4) made use of the socio-economic driven scenarios developed by the IPCC (2000). These scenarios resulted from specific socio-economic scenarios from storylines including future demographic and economic development, regionalization, energy production and use, technology, agriculture, forestry and land use (Cubasch et al., 2013). Even though the scenarios from the Special Report on Emissions Scenarios have been productive (Moss et al., 2010), new scenarios were needed. A decade worth of new data, economic, environmental, and new technologies had to be incorporated in these new scenarios.

For AR5, multiple Representative Concentration Pathway (RCP) scenarios were developed. These scenarios specify concentrations and corresponding emissions, but are not directly based on socio-economic storylines as were the scenarios used in AR4. However, these RCP scenarios can potentially be realized by more than one socio-economic scenario (Collins et al., 2013). A set of four RCP scenarios has been developed and is used as a basis for long-term and near-term modeling experiments (Van Vuuren et al., 2011), the four RCP scenarios are further explained in appendix A1. Table 1 shows the predicted global temperature change for the years 2050 and 2100 under the four RCP scenarios.

Table 1: The four RCP scenarios and predicted global temperature increase by 2050 and 2100 (data from van Oldenborgh et al., 2013). **A more extensive look into global temperature change for the RCP scenarios can be found in appendix A2.**

Scenario	Temperature increase by 2050	Temperature increase by 2100
RCP 2.6	1.00 °C	0.96 °C
RCP 4.5	1.32 °C	1.89 °C
RCP 6.0	1.16 °C	2.43 °C
RCP 8.5	1.77 °C	4.16 °C

Projections based on the SRES A1B scenario show that it is likely that the global frequency of tropical cyclones will either decrease or remain as they are now. The mean intensity, which is measured by the maximum wind speed, will increase between +2 and +11 percent. Associated rainfall rates can increase by as much as 20 percent within a radius of 100 km of the cyclone center.

3.2. Regional climate change

"Regional climates are the complex outcome of local physical processes and the non-local responses to large-scale phenomena such as the El Niño-Southern Oscillation (ENSO) and other dominant modes of climate variability" (Christensen et al., 2013).

3.2.1. Regional temperature

The North American climate is affected by 7 major climate phenomena, these climate phenomena influence aspects of the North American climate such as temperature and precipitation (Christensen et al., 2013). What these climate phenomena are and what their effects on the climate projections are, is not relevant. However, what is relevant is that these climate phenomena cause the expected increase in surface temperature change for the 21st Century for Eastern North America to deviate from the global mean surface temperature change. Figure 5 shows the multi-model mean surface temperature change for Eastern North America, where the study area is located.

The patterns observed in Figure 5, where RCP 2.6 shows stabilization in global warming, RCP 4.5 shows higher warming than RCP 6.0 until 2065 and RCP 8.5 shows by far the highest warming for the year 2100 resembles the patterns of warming of the global multi model mean surface temperature change (Figure 31, appendix A2).

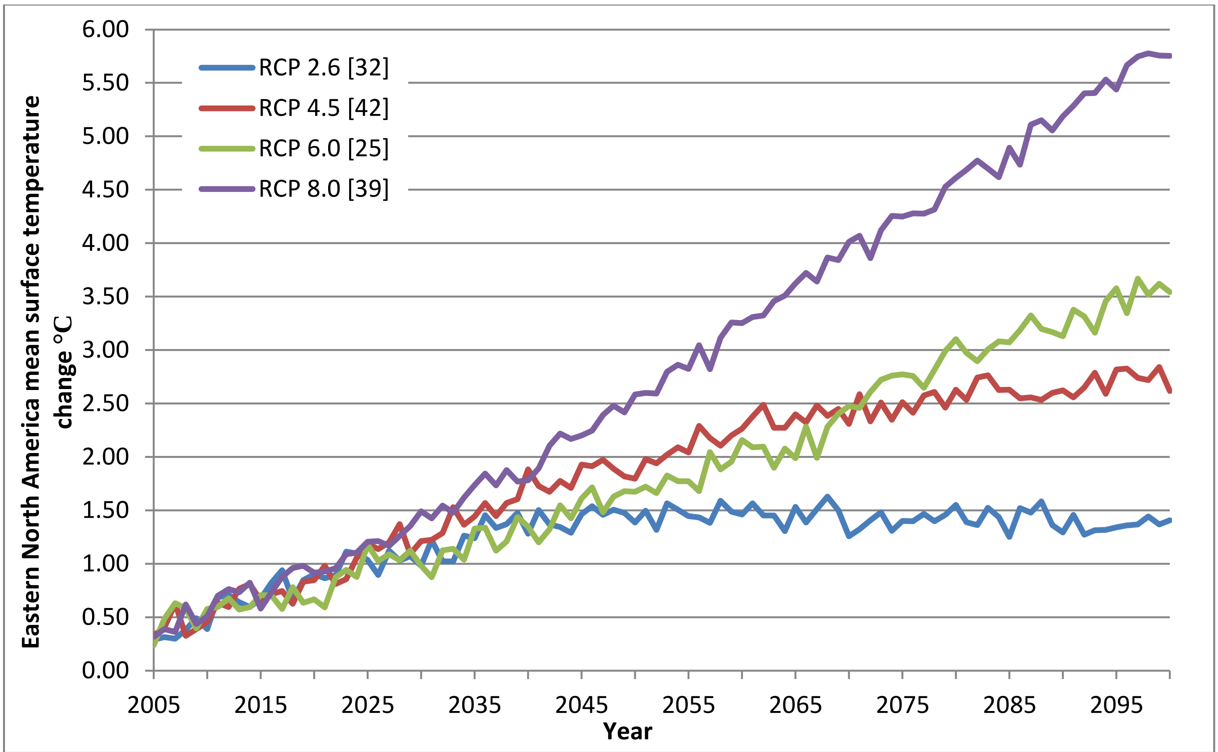

Figure 5: Multi model mean of Eastern North America mean surface temperature change for the four RCP scenarios relative to 1986-2005. Number of models per scenario can be found in the brackets (data from van Oldenborgh et al., 2013)**.**

3.2.2. Cyclones

Cyclones are also named typhoons or hurricanes. The term typhoon is used for cyclones occurring in the Pacific Ocean and the word hurricane is used for cyclones in the Atlantic Ocean. Two different types of cyclones can be distinguished: the tropical cyclone and the extra-tropical cyclone. A tropical cyclone is a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and definite cyclonic surface wind circulation (Landsea, 2011). An extra-tropical cyclone 'is a storm system that primarily gets its energy from the horizontal temperature contrasts that exist in the atmosphere. Extra-tropical cyclones are low pressure systems with associated cold fronts, warm fronts, and occluded fronts (Goldenberg, 2004). Structurally, tropical cyclones have their strongest winds near the earth's surface, while extra-tropical cyclones have their strongest winds near the tropopause - about 12 km up. These differences are due to the tropical cyclone being "warm-core" in the troposphere (below the tropopause) and the extra-tropical cyclone being "warm-core" in the stratosphere (above the tropopause) and "cold-core" in the troposphere. "Warm-core" refers to being relatively warmer than the environment at the same pressure surface (Goldenberg, 2004).

3.2.2.1. Tropical cyclones

Assessing changes in regional tropical cyclone frequency is still limited because confidence in projections critically depend on the performance of control simulations, and current climate models still fail to simulate observed temporal and spatial variations in tropical cyclone frequency (Christensen et al., 2013). A downscaling study done by Bender et al. (2010) suggests that the predicted increases in the frequency of the strongest Atlantic storms may not emerge as a statistically significant signal until the latter half of the 21st century.

3.2.2.2. Extra-tropical cyclones

Climate change studies have shown that precipitation is projected to increase in extra-tropical cyclones despite there being no increase in wind speed or intensity of extra-tropical cyclones. (Christensen et al., 2013)

3.3. Sea level rise

Sea level rise over the coming centuries is amongst the potentially most serious climate change related impacts (Jevrejeva, Moore, & Grinsted, 2012; Vermeer & Rahmstorf, 2009). The economic costs and the social consequences related to coastal flooding and forced migration will probably be one of the most important impacts of global warming (Sugiyama, Nicholls, & Vafeidis, 2008). Paleolithic sea level records from the warm periods which occurred during the last 3 million years have indicated that the global mean sea level (GMSL) exceeded 5 meters above present GMSL records. However, the global mean temperature during these warm periods was only up to 2°C warmer than pre-industrial levels (Church et al., 2013). To put this into context, the projected global mean temperature change under RCP 6.0 by the year 2100 is 2°C and the 5% confidence interval for RCP 8.5 for the year 2100 is already well beyond the 2°C mark (IPCC, 2013).

3.3.1. Global sea level rise

The primary contributions to changes in the volume of water in the oceans are the expansion of the ocean water as it warms and the transfer of water currently stored on land into the oceans, mainly from glaciers and ice sheets. Water impoundment in reservoirs and ground water depletion (and its subsequent runoff to the ocean) also affects the mean sea level (Stocker et al., 2013). Since the late 1800s, tide gauges throughout the world have shown that global sea level has risen by about 20 centimeters on average. This recent rise is much greater than at any time in at least the past 2000 years. Since 1992, the rate of global mean sea level rise measured by satellites has been roughly twice the rate observed over the last century (Walsh et al., 2014). The rate of GMSL rise during the 21st century will most likely exceed the rate of GMSL rise observed during the last 40 years for all RCP scenarios. This is due to increases in ocean warming and loss of mass from glaciers and ice sheets.

Table 2: Global mean sea level rise (m) with respect to 1986–2005 at 1 January on the years indicated. Values shown as median [likely range]. (IPCC, 2013)

Year	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
2007	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]
2010	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]
2020	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.11]
2030	0.13 [0.09 to 0.16]	0.13 [0.09 to 0.16]	0.12 [0.09 to 0.16]	0.13 [0.10 to 0.17]
2040	0.17 [0.13 to 0.22]	0.17 [0.13 to 0.22]	0.17 [0.12 to 0.21]	0.19 [0.14 to 0.24]
2050	0.22 [0.16 to 0.28]	0.23 [0.17 to 0.29]	0.22 [0.16 to 0.28]	0.25 [0.19 to 0.32]

Table 2 shows the GMSL rise in meters with respect to 1986-2005 as projected by the IPCC in AR5. The sum of the projected contributions gives the likely range for future global mean sea level rise. The median projections for GMSL in all scenarios lie within a range of 0.05 m until the middle of the century; the divergence of the climate projections has a delayed effect because oceans take a long time to respond to warmer conditions at the Earth's surface. However, predicting the behavior of large ice sheets and glaciers is still limited by a lack of understanding of the physical processes and to a lesser degree computing power (Jevrejeva et al., 2012; Vermeer & Rahmstorf, 2009; Walsh et al., 2014). Vermeer & Rahmstorf (2009) realized that AR4 did not include rapid ice flow changes in its projected sea level ranges, arguing that they could not yet be modeled, and consequently did not present an upper limit of the expected rise. In response they proposed a simple relationship linking global sea level variations to global mean temperature.

If the method presented by Vermeer & Rahmstorf (2009) presents a reasonable approximation, then mean sea levels will rise approximately three times as much by the year 2100 as is projected in AR4. Figure 6 shows their projections for three IPCC Special Report on Emission Scenarios (SRES) scenarios. Even though there has been significant improvement in accounting for important physical processes in ice-sheet models for AR5 compared to AR4, significant uncertainties remain, particularly related to the magnitude and rate of the ice-sheet contribution for the 21st century (Church et al., 2013).

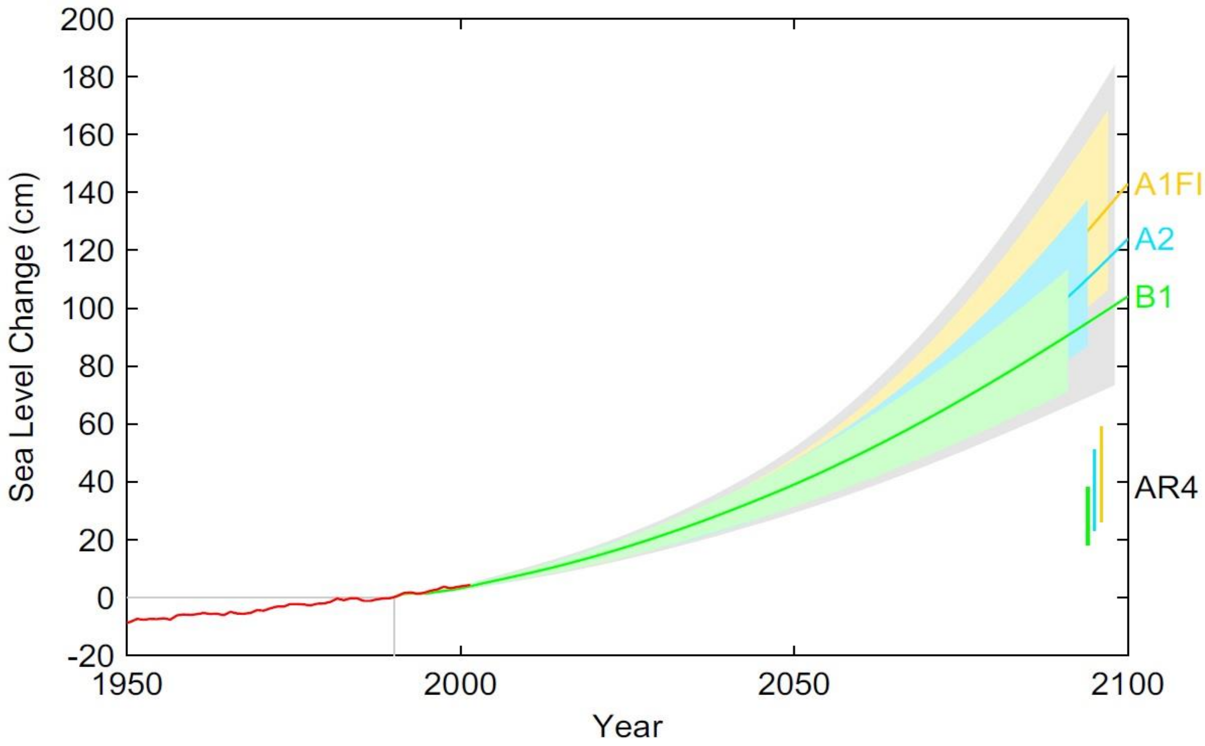

Figure 6: Projections of sea level rise by Vermeer & Rahmstorf (2009) **from 1990 to 2100, based on three different emissions scenarios from the IPCC's special report on emission scenarios (SRES). The sea level range projected in the IPCC AR4 is shown, for comparison, in the bottom right hand corner** (Vermeer & Rahmstorf, 2009)**.**

3.3.2. Regional sea level rise

Regional sea level changes may differ substantially from the global mean sea level rise. Regional factors may cause the local land or sea floor to move vertically and dynamic changes in ocean circulations can cause a local difference in sea level rise as well (Church et al., 2013; N.C. Coastal Resources Commision's Science Panel in Coastal Hazards, 2010; Parris et al., 2012). Parris et al. (2012) proposed a template for developing regional sea level rise scenarios, see Table 3. Regional sea level change is caused by a combination of three different components: global mean sea level rise, which can be taken from Table 2, and the local vertical land movement and the regional ocean basin trend, both will be discussed in the following two paragraphs.

Table 3: Template for developing regional sea level scenarios(Parris et al., 2012)**.**

Contributing Variables	Scenarios of sea level change			
	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Global mean sea level rise	22 cm	23 cm	23 cm	25 cm
Vertical Land Movement (Subsidence or uplift)	1 mm yr^{-1}	1 mm yr^{-1}	1 mm yr^{-1}	1 mm yr^{-1}
Ocean Basin Trend (from tide gauges and satellites)	0 mm yr^{-1}	0 mm yr^{-1}	0 mm yr^{-1}	0 mm yr^{-1}
Total regional sea level change	26.5 cm	27.5 cm	27.5 cm	29.5 cm

3.3.2.1. Vertical land movement

Vertical land movement is made up of three components: Glacial Isostatic Adjustment (GIA), any tectonic effect, and the total (net) effect of local processes such as sediment consolidation. However, vertical land movements are primarily associated with GIA (Engelhart, Horton, & Kemp, 2011). GIA is the response of the solid Earth to the changing surface load brought about by the increase and decrease of large-scale ice sheets and glaciers. In the past 20,000 years ice melting and associated GIA have caused up to several hundred meters of relative sea-level rise in different parts of North America (Sella et al., 2007). GIA has been estimated to be 1 mm yr^{-1} for North Carolina (Engelhart et al., 2011; Kemp et al., 2011). The tectonic component along the Atlantic coast has been widely accepted as being zero or very small and has been constant. The effect of local processes is zero to negligible (Engelhart et al., 2011). The vertical land movement for North Carolina is dependent on the GIA and thus has a magnitude of 1 mm yr^{-1}, the vertical land movement is independent of the RCP scenarios.

3.3.2.2. Ocean Basin Trend

Satellite measurements reveal important variations in the global mean sea level between and within ocean basins. Large scale climate patterns which fluctuate over decades, such as the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), and ENSO, may cause variations in the Pacific Ocean, the Gulf of Mexico, and the Atlantic Ocean (Parris et al., 2012). Research done by Sallenger, Doran & Howd (2012) and Boon (2012) found evidence of accelerated sea level rise for a hotspot along the U.S. Atlantic coast along a 1000 km stretch from Cape Hatteras (North Carolina), to above Boston (Massachusetts). However, for the area south of Cape Hatteras (Beaufort is located roughly 150 km south of Cape Hatteras) the accelerated sea level rise is negligible (Sallenger, Doran, & Howd, 2012).

3.3.2.3. Total regional sea level change

The total regional sea level change for the four RCP scenarios can finally be calculated based on the above mentioned scenarios for global sea level rise (Table 2), vertical land movement and the ocean basin trend. The results for the expected regional sea level changes for each of the climate change scenarios are presented in Table 3.

3.4. Hurricanes

In chapter 3.2.2 the difference between tropical and extra-tropical cyclones was made. One of the key differences between these two is that tropical cyclones have their strongest winds near the earth's surface , while extra-tropical cyclones have their strongest winds near the tropopause - about 12 km up (Goldenberg, 2004). Because of this difference this paragraph will only assess the climate impacts related to tropical cyclones.

The climate change impacts to hurricanes are mainly resulting in changing hurricane frequencies (Christensen et al., 2013), giving rise to future changes of the return periods for all categories of hurricanes. The focus of the climate impacts related to hurricanes is the return period for all categories of hurricanes for North Carolina in the year 2050.

3.4.1. Current North Carolina return period

In order to determine the climate change impacts on hurricanes, the first step is to determine the current hurricane strength associated with storms with return periods of 100 years and 500 years. Appendix B1 shows data regarding all hurricanes that made landfall between the states of Texas and Maine during the 1900-2013 period, as retrieved from the Atlantic Oceanographic & Meteorological Laboratory: Hurricane Research Division (2014). This is the data used in determining the wind speeds that are currently associated with a 100 year storm and a 500 year storm.

This section shows the step by step process of determining the wind speeds that are currently associated with a 100 year storm and a 500 year storm. The current wind speed associated with the 100 year storm is 130 knots or 241 km/h, for the 500 year storm this is 156 knots or 289 km/h.

In order to calculate the wind speed associated with the current hurricane return period for North Carolina a number of steps need to be taken, these steps are systematically explained below.

Step 1 – In order to calculate the return periods the hurricane wind speed is required. All hurricanes for which the wind speed at landfall cannot be obtained are removed from the list. This gives Table 4 as an updated version of Table 12 (appendix B1).

Table 4: Updated from Table 12 to only show hurricanes for which wind speed can be obtained.

Category	Total
Category 1 Hurricanes	80
Category 2 Hurricanes	42
Category 3 Hurricanes	43
Category 4 Hurricanes	18
Category 5 Hurricanes	3
All Hurricanes	186
Total hurricanes to hit North Carolina	37

Step 2 – The storm categories 1 through 5 are divided into smaller categories to increase the number of data points. Category 1 starts with the smallest wind speed, 64 knots, and increases with steps of five knots. Some steps have a smaller or larger increase than 5 knots, this is due to the fact that there are fewer than 5 knots remaining within a storm category or the fact that an increment of 5 knots has no storm occurrences. The categories can be viewed in Table 5 (columns 2 and 3).

Step 3 – The number of hurricanes occurring within each of the categories is counted and an inverse cumulative function is based on the frequency, this can be seen in Table 5 (columns 4 and 5). The inverse cumulative distribution denotes that for a certain category of storms there is a number of storms equal to or greater than the wind speed for this category.

Step 4 – 186 storms have made landfall in the U.S. anywhere from Texas to Maine over a 113 year period. Dividing the 113 year period by the number of storms equal to or greater than a certain wind speed (column 5) yields the return period for a storm with a certain minimum wind speed, see Table 5 (column 6) for the return periods. 37 out of 192 storms hit North Carolina or 19.27% of storms. The results from column 6 are divided by 0.1927, the result is the return period for North Carolina shown in column 7.

Step 5 – The results from Table 5 column 7 are plotted in Figure 7 (an expanded figure can be found in Figure 32 appendix B2). Based on these computations, the 100 year storm has wind speeds starting at 129.6 knots, the 500 year storm has wind speeds starting at 156.4 knots.

Table 5: Revised storm categories (columns 1,2, and 3), number of storms per category and inverse cumulative distribution of storms (columns 4 and 5), return period for storms in the U.S. and for North Carolina (columns 6 and 7).

Storm Category	Windspeed min (knots)	Windspeed max (knots)	Frequency	Inverse cumulative	Years per storm	Years per storm in NC
1-1	64	< 69	24	186	0.608	3.153
1-2	69	< 74	22	162	0.698	3.620
1-3	74	< 79	22	140	0.807	4.188
1-4	79	< 83	15	118	0.958	4.969
2-1	83	< 88	15	103	1.097	5.693
2-2	88	< 93	18	88	1.284	6.663
2-3	93	< 96	10	70	1.614	8.377
3-1	96	< 101	17	60	1.883	9.773
3-2	101	< 106	11	43	2.628	13.637
3-2	106	< 113	11	32	3.531	18.324
4-1	113	< 118	8	21	5.381	27.923
4-2	118	< 123	3	13	8.692	45.106
4-3	123	< 127	4	10	11.300	58.638
4-4	127	< 137	3	6	18.833	97.730
5-1	137	< 142	1	3	37.667	195.459
5-2	142	< 156	1	2	56.500	293.189
5-3	156	< 161	1	1	113.000	586.378

3.4.2. Future North Carolina return period

Bender et al. (2010) and Knutson, Sirutis, Vecchi, Garner, & Zhao (2013) explored the influence of future global warming on Atlantic hurricanes with a downscaling strategy. This downscaling method is capable of realistically simulating category 4 and 5 hurricanes. Because the wind speeds associated with the 100 and 500 year storm are a large category 4 and a category 5, this method is applicable to our data as well. This downscaling is based on the ensemble mean of 18 global climate change projections. These 18 models are the result of the World Climate Research Program coupled model intercomparison project 3 (CMIP3) and use the IPCC SRES A1B emissions scenario with global warming for the year 2100. Table 6 shows the results of the downscaling experiments from Bender et al. (2010) and Knutson et al. (2013). These CMIP3 downscaling results will be used to determine the updated frequency of hurricanes under climate change conditions for the year 2050.

Table 6: Downscaling experiments for Atlantic hurricanes, based on comparing 27 Augustus – October seasons (1980-2006) with and without the climate change perturbation for the year 2100 and the year 2050. (Knutson et al., 2013)

Storm category	Ensemble warmed climate 2100 (percent change)	Ensemble warmed climate 2050 (percent change)
Category 1	- 51.6	- 24.3
Category 2	- 17.5	- 8.2
Category 3	- 45.2	- 21.2
Category 4	+ 83.3	+ 39.2
Category 5	+ 200	+ 94

This section shows the step by step process of determining the new return periods for North Carolina in the year 2050. The return period for a storm with wind speeds starting at 130 knots (which currently has a return period of 100 years) will become 61 years and the return period for a storm with wind speeds starting at 156 knots (the current 500 year storm) would reduce to only 231 years.

The wind speed associated with the current 100 year storm and the current 500 year storm are calculated in section 3.4.1. With the hurricane frequencies changing due to the impacts of climate change, the wind speeds calculated in section 3.4.1 will have a different return period in the future. In order to calculate the new return period associated with the current wind speed for North Carolina a number of steps need to be taken, these steps are systematically explained below.

Step 6 – Under climate change conditions the frequency of occurrence for the 5 different hurricane categories will change, Table 6 shows the change in percentage per category of hurricane. The current hurricane frequencies (Table 7 column 2) are updated with the percentage change from column 3 Table 7. Column 4 Table 7 shows the updated frequencies per category.

Step7 – The number of hurricanes occurring within each of the categories is counted and an inverse cumulative function is based on the frequency, this can be seen in Table 7 (columns 4 and 5). The inverse cumulative distribution denotes that for a certain category of storms there is a number of storms equal to or greater than the wind speed for this category.

Step 8 – 186 storms have made landfall in the U.S. anywhere from Texas to Maine over a 113 year period. Dividing the 113 year period by the number of storms equal to or greater than a certain wind speed yields the return period for a storm with a certain minimum wind speed, see Table 7 (column 6) for the return periods. 37 out of 192 storms hit North Carolina, 19.27% of all storms. The results from column 6 are divided by 0.1927, the result is the return period for North Carolina shown in column 7.

Step 9 – The results from Table 7 column 7 are plotted in Figure 7 (an expanded figure can be found in Figure 32 appendix B2).

Step 10 – To determine the new return period associated with the wind speeds calculated in step 5, an exponential trend line is added to the data points. The wind speed from step 5 is used in combination with the trend line to determine the new corresponding return period. The old 100 year storm with wind speeds of 129.6 knots has a return period of 61 years under climate change conditions by the year 2050. The old 500 year storm with wind speeds of 156.4 knots has a return period of 231 years under climate change conditions by the year 2050.

Table 7: Number of storms per category, number of storms per category with climate change, and inverse cumulative distribution of storms (columns 2,3, and 4), return period for storms in the U.S. and for North Carolina (columns 5 and 6).

Storm Category	Frequency (1900-2013)	Frequency change due to climate change (for 2050)	Climate change updated frequency	Inverse cumulative	Years per storm	Years per storm in NC
1-1	24	-24%	18.18	163.92	0.689	3.577
1-2	22	-24%	16.66	145.74	0.775	4.024
1-3	22	-24%	16.66	129.07	0.875	4.543
1-4	15	-24%	11.36	112.41	1.005	5.217
2-1	15	-8%	13.77	101.05	1.118	5.803
2-2	18	-8%	16.52	87.28	1.295	6.718
2-3	10	-8%	9.18	70.76	1.597	8.287
3-1	17	-21%	13.39	61.58	1.835	9.522
3-2	11	-21%	8.66	48.19	2.345	12.167
3-2	11	-21%	8.66	39.53	2.859	14.834
4-1	8	+39%	11.13	30.87	3.661	18.997
4-2	3	+39%	4.17	19.74	5.726	29.712
4-3	4	+39%	5.57	15.56	7.262	37.684
4-4	3	+39%	4.17	9.99	11.306	58.670
5-1	1	+94%	1.94	5.82	19.416	100.752
5-2	1	+94%	1.94	3.88	29.124	151.128
5-3	1	+94%	1.94	1.94	58.247	302.257

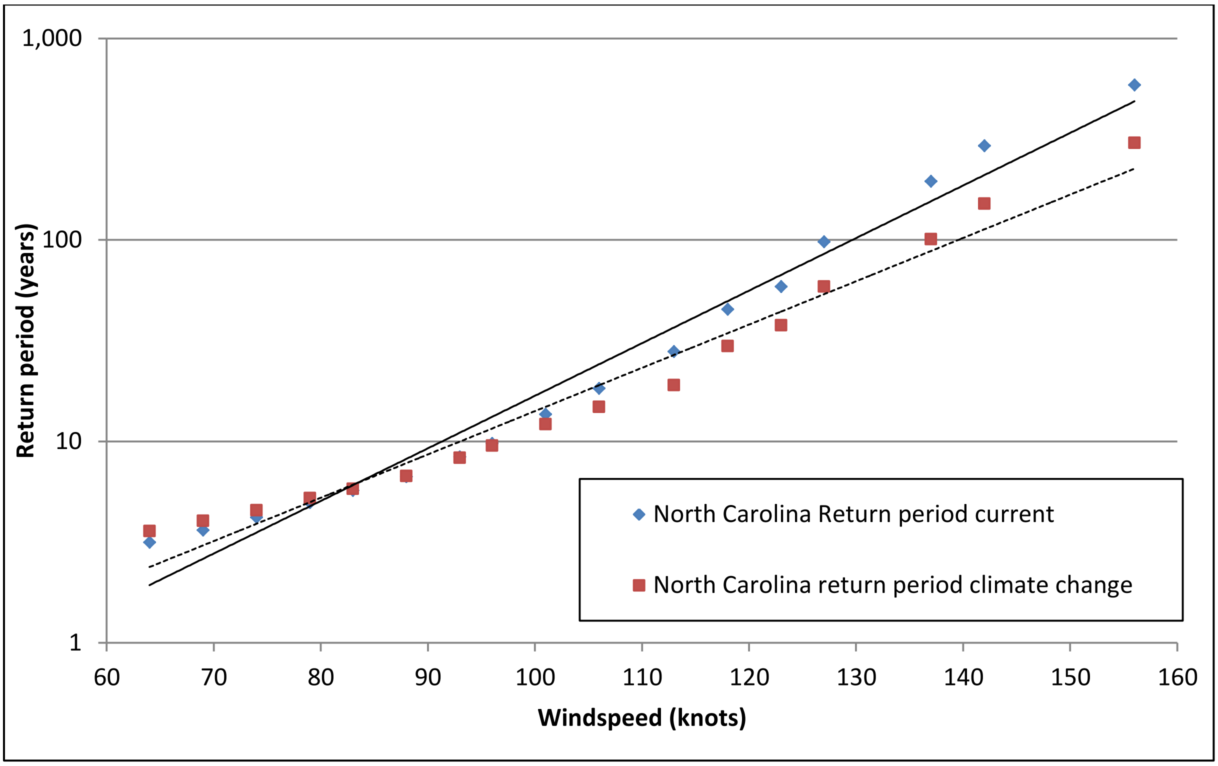

Figure 7: North Carolina hurricane return period. Wind speed plotted against the return period.

4. Risk perception

Divided into three subjects, risk will be explored by taking a look at objective risk, subjective risk, and the way risk is incorporated into the RHEA model. The objective risk shows the actual risk. The subjective risk goes into the theory of how housing market actors observe risk. Both kinds of risk will be addressed in this chapter. This chapter concludes by showing how risk perception bias (i.e. subjective risk) has been added to the RHEA model.

4.1. Objective risk

Within this research objective risk is defined as the actual flood risk probability, the Federal Emergency Management Agency (FEMA) is responsible for determining the flood risk probability in the United States. In accordance with the National Flood Insurance Program (NFIP) FEMA defines geographical areas according to varying levels of flood risk. Three different types of flood zones can be defined for the coastal area: (i) high risk zones, coastal areas with a 1:100 flood probability; (ii) moderate risk zones, coastal areas with a 1:500 flood probability; and (iii) low risk zones, coastal areas determined to be outside of the 1:500 probability flood zone (Michel-Kerjan, 2010). The latest flood maps for Beaufort have been created in 2003.

For Carteret County the dominant source of flooding are wind driven storm surges associated with hurricanes (Carteret County, n.d.). For Beaufort no other source of flooding could be determined. The assumption is made that under current conditions a hurricane with a return period of a 100 years is responsible for flooding the 1:100 flood zone and a hurricane with a return period of 500 years would be responsible for the flooding of the 1:500 flood zone (section 3.4.1.). The return periods and associated flooding probabilities under climate change conditions have been determined in section 3.4.2.

4.2. Subjective risk

Housing market actors will assess objective flood risk on the basis of probability and severity of damage, these are biased by myopia and amnesia. Under these two principles it could mean that subjective risk can diverge considerably from objective risk, especially if a long time has passed since a local flood event has occurred. In this section the principles of myopia and amnesia, and the housing market response to these principles will be discussed.

4.2.1. Myopia

Myopia is the discounting of information for anticipated future events. The discounting will rise progressively as the event becomes less anticipated (Pryce et al., 2011). Four main reasons exist why it can be expected that information regarding the future will be discounted.

First, a negative relationship can exist between temporal distance and the perceived importance of information. Predictions of rising flood risks for 5, 10 or 20 years into the future might be met with inattention/disregard and as a result, future flood risk may not have any noticeable influence on current property value. An individual may assess the likelihood of an event to be higher when examples come to mind more readily. Therefore it might be hard to imagine such events happening in the distant future. Second, the public has a tendency to distrust the information about the future since they believe these are attempts by vested interests to exert power (Pryce et al., 2011) and they might just disagree with what scientists are telling them (Kahan, Jenkins-Smith, & Braman, 2011). Third, climate models are highly technical and their outcomes are probabilistic. Limited understanding leads to an inability of people to respond appropriately to data in terms of density functions and dependent scenarios. Finally, purchasing a house does not occur under ceteris-paribus conditions. Buying a house is a process riddled with emotions, hopes, ambitions, and imagined lifestyle aspirations on which the dangers of future flooding have little influence (Pryce et al., 2011).

4.2.2. Amnesia

In contrast to myopia, amnesia is the discounting of information from past events, with the discount rising progressively as time elapses. Households weigh recent flood information more heavily than they do with floods that happened a long time ago, the risks of flooding will be overestimated right after a flood but declines quickly as time passes without re-occurring flood events (Pryce et al., 2011). The cognitive effects of flooding disappear within a 5 to 6 year period (Bin & Landry, 2013).

An important consideration in this respect is the difference between individual amnesia and market amnesia. Even though individual households might be perfectly aware of flood risks potential buyers coming from outside the area may not be. Information asymmetry may be exacerbated by home owners and real estate agents who conceal flood risks in an attempt to stop the reduction in property values (Pryce et al., 2011).

4.2.3. Housing market response to myopia and amnesia

In this section, we will take a look at the housing market response to flood risk under myopia and amnesia. Figure 8 serves as a starting point, it depicts an efficient housing market with fully risk-adjusted prices. Figure 8 shows how floods at t_{F1} and t_{F2} only have a temporary effect on observed property values (P_A). This holds true for a particular area in which the market valuations are fully risk-adjusted, in other words where people have an objective view of risk. Because the occurrence of a flood does not change the objective flood risk, the value of a house is not lowered because of the flood other than a temporary reduction in quality of the house due to damages done by the flood (Pryce et al., 2011).

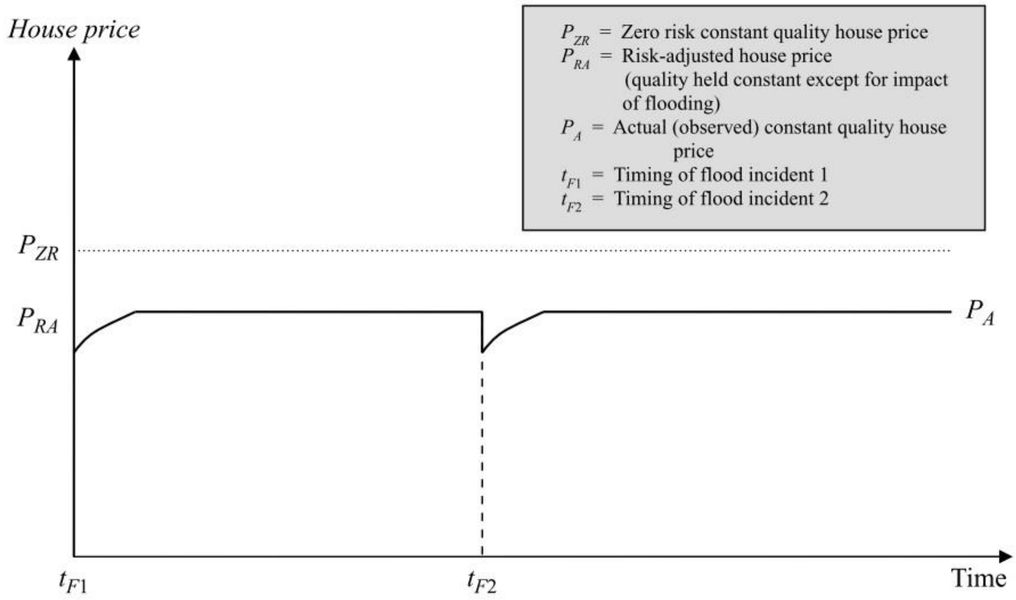

Figure 8: Fully risk-adjusted prices and short-run responses to flooding (Pryce et al., 2011)

Figure 9 shows a world of imperfect information. In this situation the house price will drift from the risk adjusted house price to the zero risk house price in the years following a flood event, due to changing subjective risk as a result of myopia and amnesia. When a flood event occurs, the market will suddenly become aware of the flood risk and adjust the house price downward to the risk adjusted house price. It is even possible in the immediate aftermath of a flood for future flood risks to be overestimated, leading to a drop below the (objective) risk adjusted house price.

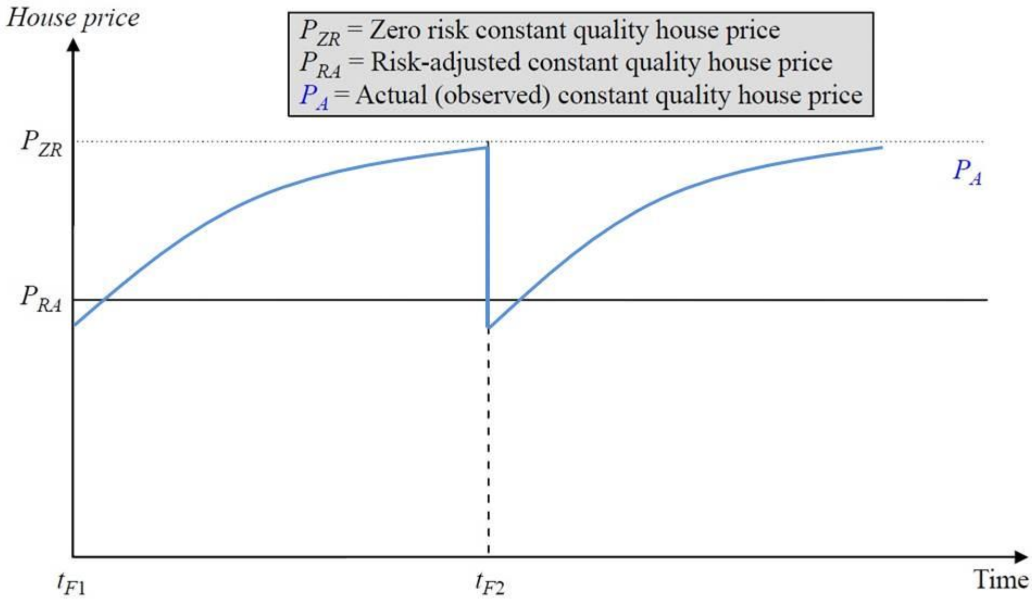

Figure 9: House prices with myopia and amnesia (adapted from Pryce et al., 2011)

4.3. Risk perception bias procedure

Myopia and amnesia need to be incorporated into the RHEA model so that the property values follow the general time-dependency from Figure 9 and hence represent (subjective) risk perception bias. In order to do this, the RHEA model is extended. This addition can be found in appendix D2. This part of the code will allow for risk perception bias to be related to a flood event. Three new variables have been introduced in the risk perception bias code to allow the myopia and amnesia to be incorporated into the RHEA model, their functions are discussed below.

"counter" – The counter counts the time steps that have passed since a flood event. From Pryce et al. (2011) and Bin & Landry (2013) we find that people 'forget' what has happened after a period of five years, the current counter has been set to count 10 semi-annual time steps for a total of five years. The counter is reset when a flood event has happened.

"perception_change" – Right after a flood event the perception of risk will be highest and as a result the property values at this time will be the lowest, as can be seen in Figure 9. With *perception_change* the individual risk perception bias can be set for the time right after a flood event.

"DC" – The discount coefficient allows the *perception_change* to be discounted over 10 time steps from a state of maximum risk perception bias to a state of 'zero risk'. This parameter represents the gradual decrease of the risk perception bias when time since the latest flood passes.

From Bin & Landry (2013) we saw that the discount factor follows a logarithmic curve, so it was decided that the risk perception bias should also have a logarithmic curve. In Figure 10 we see the logarithmic curve used for discounting.

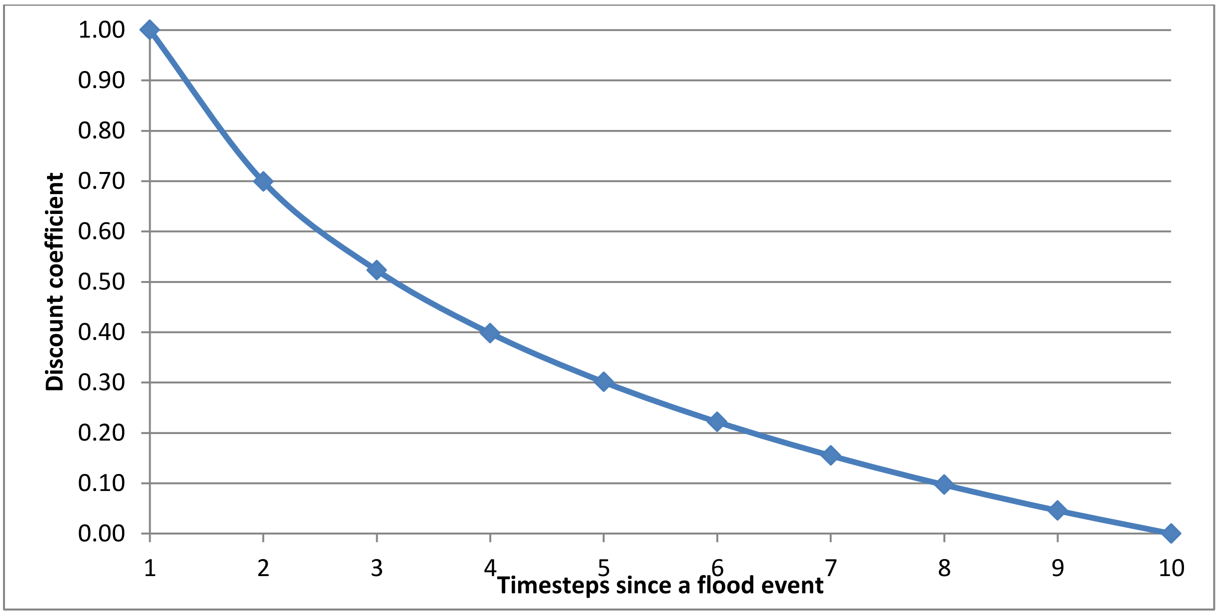

Figure 10: Logarithmic discount coefficient curve providing discount coefficients for calculating perceived flood risks after a flood event.

The perception code functions as follows.

1. The procedure checks if the counter has a value of <= 10, if this is not the case, the A-RPbias is set to zero since the assumption is made that people live in a 'zero risk' world (Pryce et al., 2011). The current procedure assumes that it takes five years for the risk perception bias to recover and reach 'zero risk' perception.

2. The procedure checks if ‘sameRPbias’ is set to true, if this is the case A-RPbias will be the same for everybody. In this case A-RPbias is determined by taking the value for DC for the right time step and is multiplied with perception_change.
3. If ‘sameRPbias’ is false, the calculation for A-RPbias takes an extra step. The curve from Figure 10 is used, again with the value assigned to the slider ‘perception_change’. A normal distribution of A-RPbias is assumed with:
    a. Mean (DC * perception_change)
    b. Standard deviation ((DC * perception_change) * (1/6))

   The A-RPbias is normally distributed and randomly assigned to agents, and uses a mean which is equal to the A-RPbias if ‘sameRPbias’ is set true, as seen in step 2.
4. A check is carried out to make sure A-RPbias is either larger than 0 or smaller than 1.

With this procedure every buyer and seller is assigned a value for his risk perception bias.

5. Scenario analysis

This chapter will start with the definition of the scenarios that will be used in the simulations with the RHEA model. Next the results of these simulations will be displayed and analysed. The analysis of these results will serve as the basis for the discussion and conclusion in the subsequent chapters, aiming to answer the research objective.

5.1. Scenarios

In order the quantify the effect of climate change, associated flood risks and risk perception bias on coastal urban property values, four scenarios have been developed to be simulated using the RHEA model. The four scenarios allow for varying between climate change and steady-state climatic conditions, and for differentiating between market participants with perfect information and the ones whose risk perceptions are biased. Each scenario simulates a period of about 50 years, from 2003 until 2050. The choice for 2003 as a starting point has been made because the current flood maps and associated flood risks have last been updated by FEMA in 2003. In order to be able to incorporate risk perception bias, a flood event has to happen to start the risk perception bias procedure (section 4.3). To achieve this, two flood events have been added, one after 10 semi-annual time steps (5 years) and one after 60 semi-annual time steps (30 years) from the start of the simulation.

5.1.1. Scenario 1

The first scenario serves as a baseline scenario, applying steady-state climatic conditions and accounting for objective risks only. the traders in the RHEA model operate under perfect information and assume the original (objective) flooding probabilities of 0.01 for the 100 year floodplain and 0.002 for the 500 year floodplain. Scenario 1 allows to simulate the development of property values without the interference of risk perception bias or climate change.

5.1.2. Scenario 2

In the second scenario the traders again operate under perfect information (objective risk only). However, this time traders assume the flooding probabilities will be increasing due to the impacts of climate change (section 3.4.2). This scenario therefore applies flooding probabilities of 0.0164 for the current 100 year floodplain and 0.0043 for the current 500 year floodplain. Scenario 2 allows to simulate the development of property values under climate change without risk perception bias.

5.1.3. Scenario 3

In the third scenario, climatic conditions are again assumed steady, but traders no longer operate in a world of perfect information. Instead they operate under the risk perception bias as it was determined in chapter 4.2. Scenario 3 allows to simulate the development of property values under risk perception bias, but without climate change.

5.1.4. Scenario 4

In the last scenario the traders will operate under both climate change and risk perception bias. Scenario 4 allows to simulate the combined effects of climate change and risk perception bias on the development of property values.

Table 8: An overview of the four scenarios to be simulated using the RHEA model

		Climate Change	
		No	**Yes**
Risk perception bias	**No**	Scenario 1	Scenario 2
	yes	Scenario 3	Scenario 4

5.2. Results

In this section, the results from the scenario simulations will be presented and analysed. Each scenario has been simulated with a total of 16 different random seeds , each representation of data will be the average of these 16 random seeds. The input parameters for each scenario are the same and can be found in appendix C2. For each scenario, four different flood zones are monitored, these are: the safe zone (FP0), the current 100 year floodplain without the coastal front properties (FP100noCF), the current 500 year floodplain (FP500), and the coastal front properties (CF). For each flood zone three statistics are monitored: the number of trades in each time step for every flood zone (#Trades), the total value of the trades in each time step for every flood zone (sump), and the average trade price in each time step for every flood zone (avtrp). Each result displayed here will be accompanied by a code to keep track of what it represents, these codes will be formatted as follows, '1-sump-FP100noCF'. The code is made up of three parts that are separated by a dash (-): the first part shows the scenario number, the second part the statistic being tracked, and the final part determines the flood zone at stake.

The properties in the current 100 year floodplain and the coastal front properties were separated from each other because the coastal front properties are on average 2 to 3 times more expensive than non-coastal front properties in the 100 year floodplain. By separating these two zones, it is possible to get a better representation of the development of property values in the 100 year floodplain.

All the figures showing results have been formatted in the same way, this makes comparison between graphs easier. The x-axis shows the time in the simulation and ranges from the year 2003 to the year 2050. The y-axis is uniform for all graphs with a range of 0 to 230. The y-axis has 2 meanings, first, for the total value of trades (sump) and the average trade price (avtrp) it shows indexed values, expressed as a percentage of the value of the first time step. Second for the number of trades (#Trades) it shows the number of trades.

5.2.1. The Impact of climate change on property values under perfect information

In order to determine the effects of climate change on property values in Beaufort, scenarios 1 and 2 are compared. With both scenario 1 and 2 operating under perfect information (objective risk only) the results allow to visualize the effect of climate change without the influence of risk perception bias.

Figure 11 shows nearly identical values for both scenarios during the first half of the simulated period (2003-2025). This is to be expected for the FP0 flood zone, since the utility calculations for this flood zone only calculate utilities for a no-flood situation (U_{NF} in equation 3) since these areas will never be flooded. During the second half of the simulation period (2025-2050), the average trade price and as a result the total trade volume increases. This is most likely due to the safe zone becoming a sellers' market, since the properties in the safe zone have a superior utility value. In Figure 12 the FP100noCF flood zone shows the same kind of behavior throughout the simulation. However, FP100noCF shows a higher trade volume for the same number of trades when increased flood risks are simulated. This would indicate more expensive properties being sold under climate change conditions (as is confirmed by the higher average trade price). More expensive properties would indicate, bigger properties, more bathrooms, better access to amenities etc. This means a higher utility to compensate for the diminished utility which goes along with a higher flooding probability.

Figure 13 shows that the number of trades is slightly lower under climate change conditions for the FP500 flood zone. The trade volumes for the FP500 flood zone do remain roughly equal to each other, (+/- 5% lower under climate change conditions). Combined with the higher average trade price (+/- 13 percentage points) and the slightly lower number of trades this would suggest that under climate change conditions, more expensive houses are sold. The reduction in the number of trades for the FP500 zone (under climate change conditions) can be explained by traders searching for higher utility values to compensate for the utility loss due to the increased flood risk. Higher utility can be obtained by either moving to a flood zone with a lower objective risk (FP0), purchase a property with higher amenity values (FP100noCF which is closer to the ocean) or purchase property with a higher utility value in the same flood zone. This also happens in the FP100noCF flood zone. Figure 14 shows the coastal front properties being unaffected by higher flood probabilities.

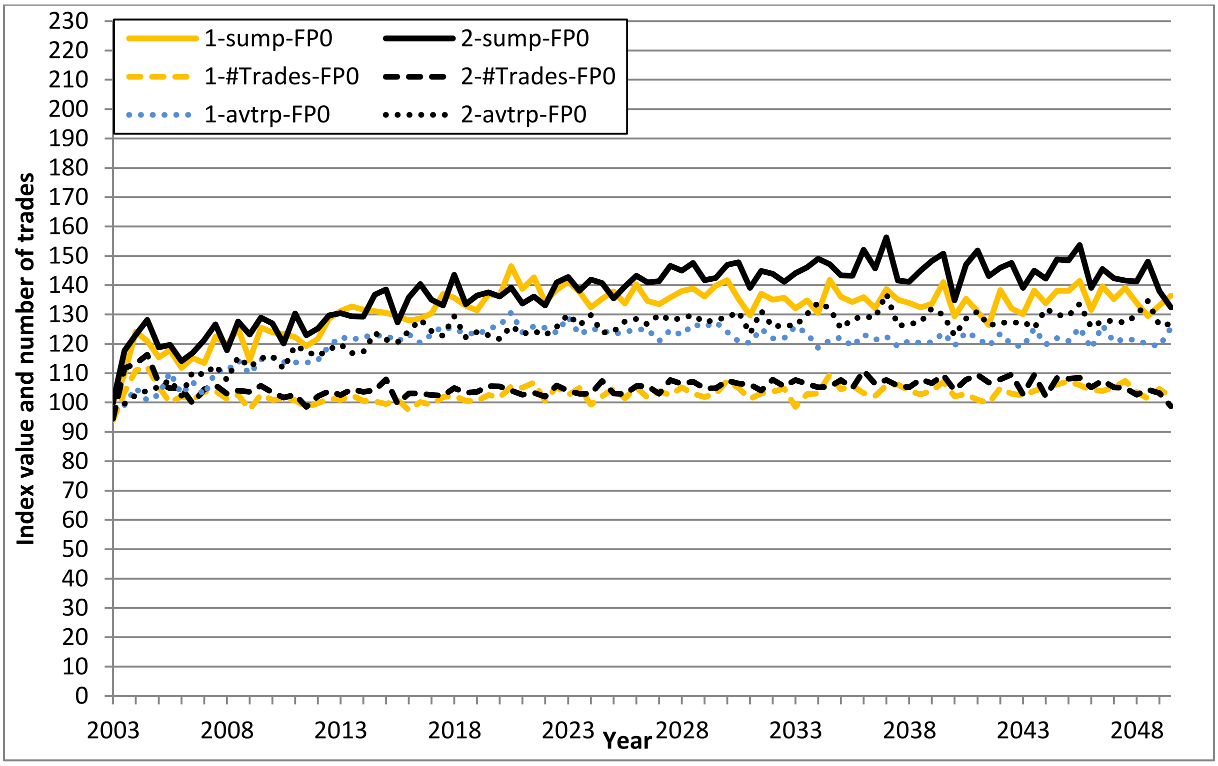

Figure 11: The impact of climate change on property values, in the safe zone (FP0), under perfect information. The following results are displayed for scenarios 1 and 2: sump - the total value of the trades in each time step for the FP0 zone, #Trades - the number of trades in each time step for the FP0 zone, and avtrp - the average trade price in each time step for the FP0 zone.

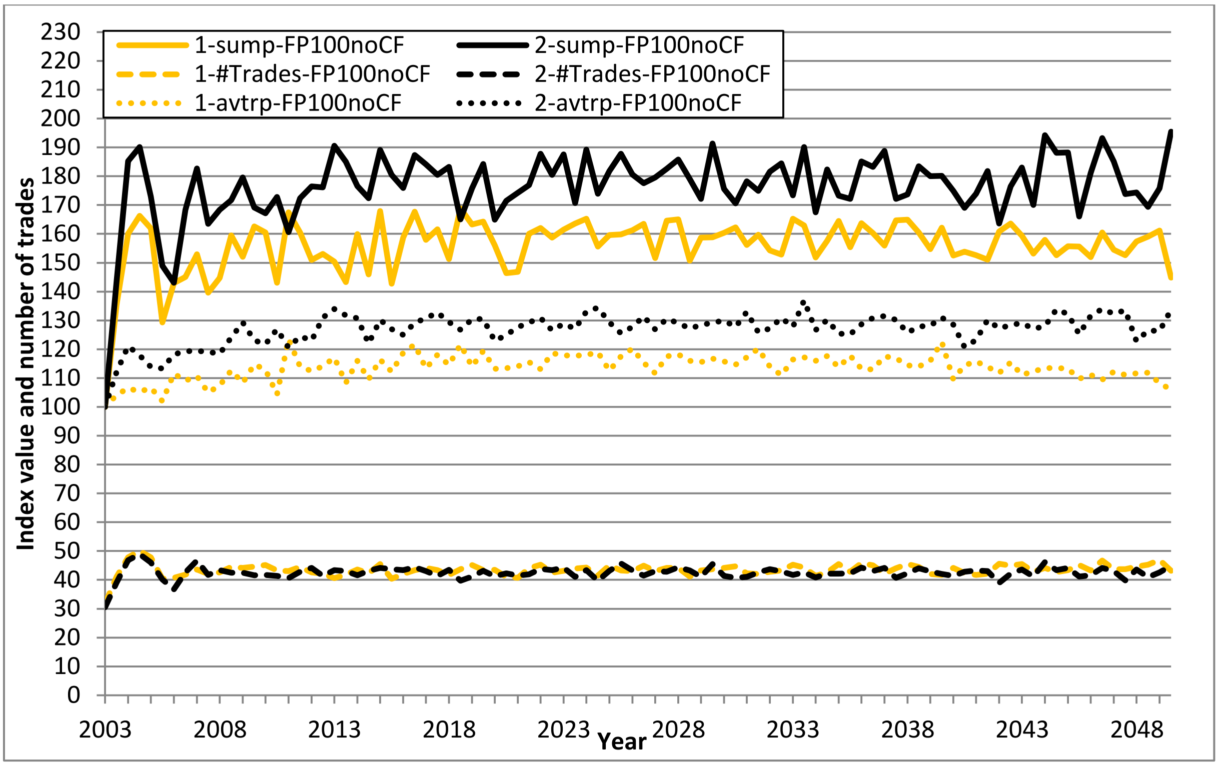

Figure 12: The impact of climate change on property values, in the current 100 year floodplain without the coastal front properties (FP100noCF), under perfect information. The following results are displayed for scenarios 1 and 2: sump - the total value of the trades in each time step for the FP100noCF zone, #Trades - the number of trades in each time step for the FP100noCF zone, and avtrp - the average trade price in each time step for the FP100noCF zone.

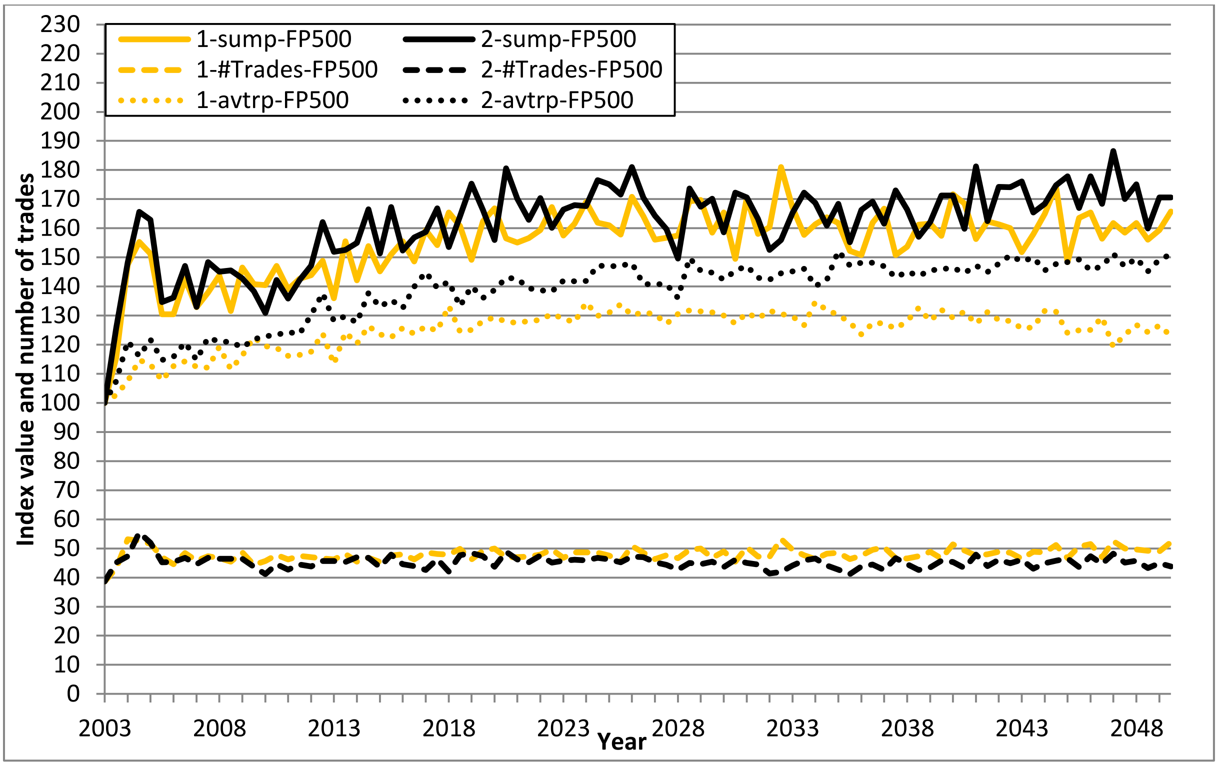

Figure 13: The impact of climate change on property values, in the current 500 year floodplain (FP500), under perfect information. The following results are displayed for scenarios 1 and 2: sump - the total value of the trades in each time step for the FP500 zone, #Trades - the number of trades in each time step for the FP500 zone, and avtrp - the average trade price in each time step for the FP500 zone.

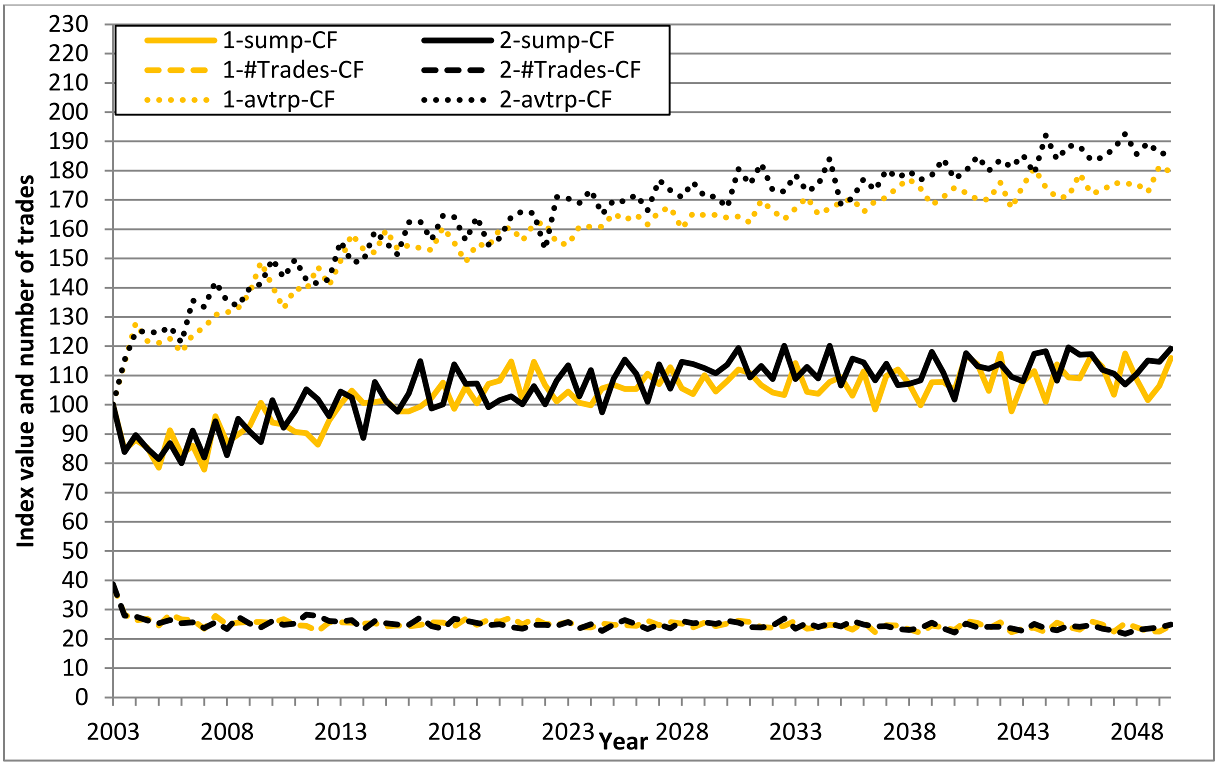

Figure 14: The impact of climate change on property values, for the coastal front properties (CF), under perfect information. The following results are displayed for scenarios 1 and 2: sump - the total value of the trades in each time step for the CF zone, #Trades - the number of trades in each time step for the CF zone, and avtrp - the average trade price in each time step for the CF zone.

5.2.2. The Impact of risk perception bias on property values under current climate conditions

In order to determine the effects of risk perception bias, scenarios 1 and 3 are compared. With both scenario 1 and 3 operating under current climate conditions the results allow to visualize the effect of risk perception bias without the influence of climate change.

For the FP0 (Figure 15), FP100noCF (Figure 16), and FP500 (Figure 17) flood zones the difference between perfect information and risk perception bias only becomes clear after a flood event has passed. The first thing to notice is the average trade price in Figure 16 and Figure 17, which drops after each flood event, compared to scenario 1. Every time a flood event has happened the difference between the average trade price between scenario 1 and 3 increases. This is especially clear for the current 500 year flood plain, before the first flood event the average trade prices are equal to each other but for the final 5 years a difference of +/- 17 percentage points can be observed. This is due to a combination of the price drop in the 5 years after a flood event and the fact that the hedonic-price-calculation uses data from 1 time step into the past to calculate new prices. With the average trade price dropping after each flood event for scenario 3 a difference in number of trades can be seen when compared to scenario 1. When the average price goes down, houses become cheaper and thus more likely to be bought, this goes for both the current 100 and 500 year floodplains where scenario 3 has a slightly higher number of trades after flooding. Consequently the FP0 zone sees an opposite trend.

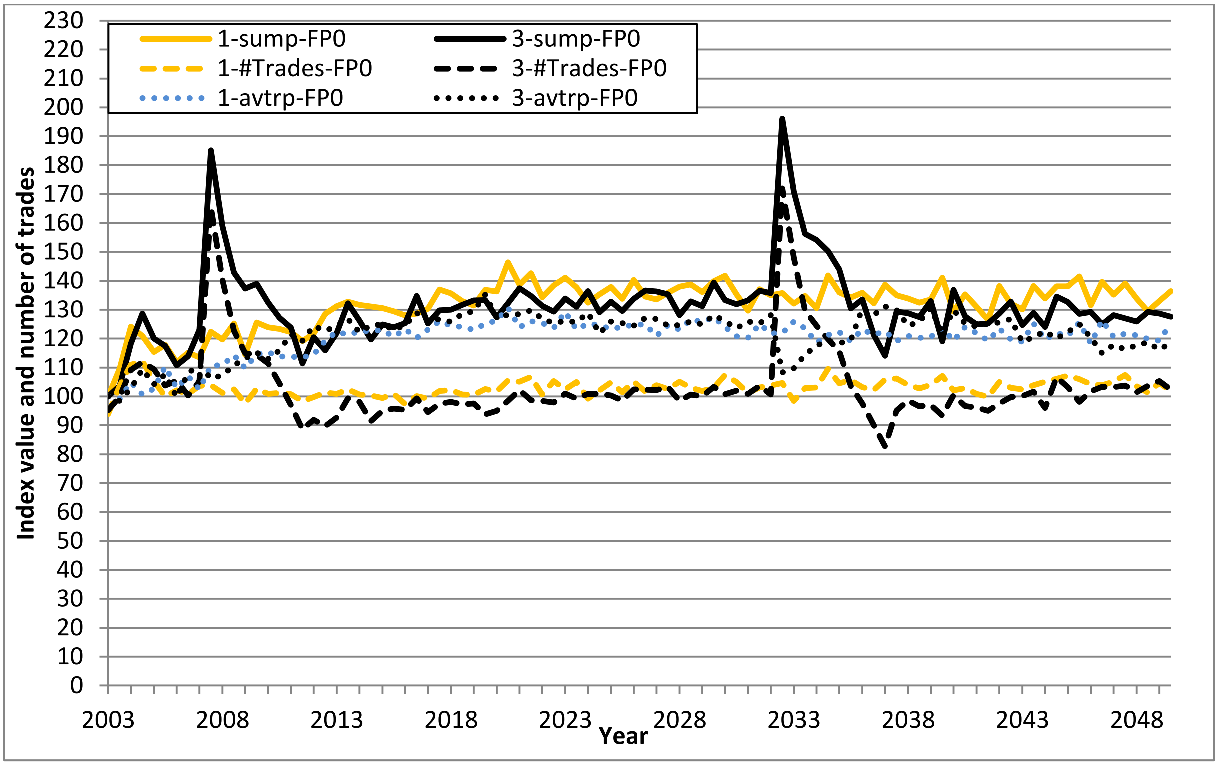

Figure 15: The Impact of risk perception bias on property values, in the safe zone (FP0), under current climate conditions. The following results are displayed for scenarios 1 and 3: sump - the total value of the trades in each time step for the FP0 zone, #Trades - the number of trades in each time step for the FP0 zone, and avtrp - the average trade price in each time step for the FP0 zone.

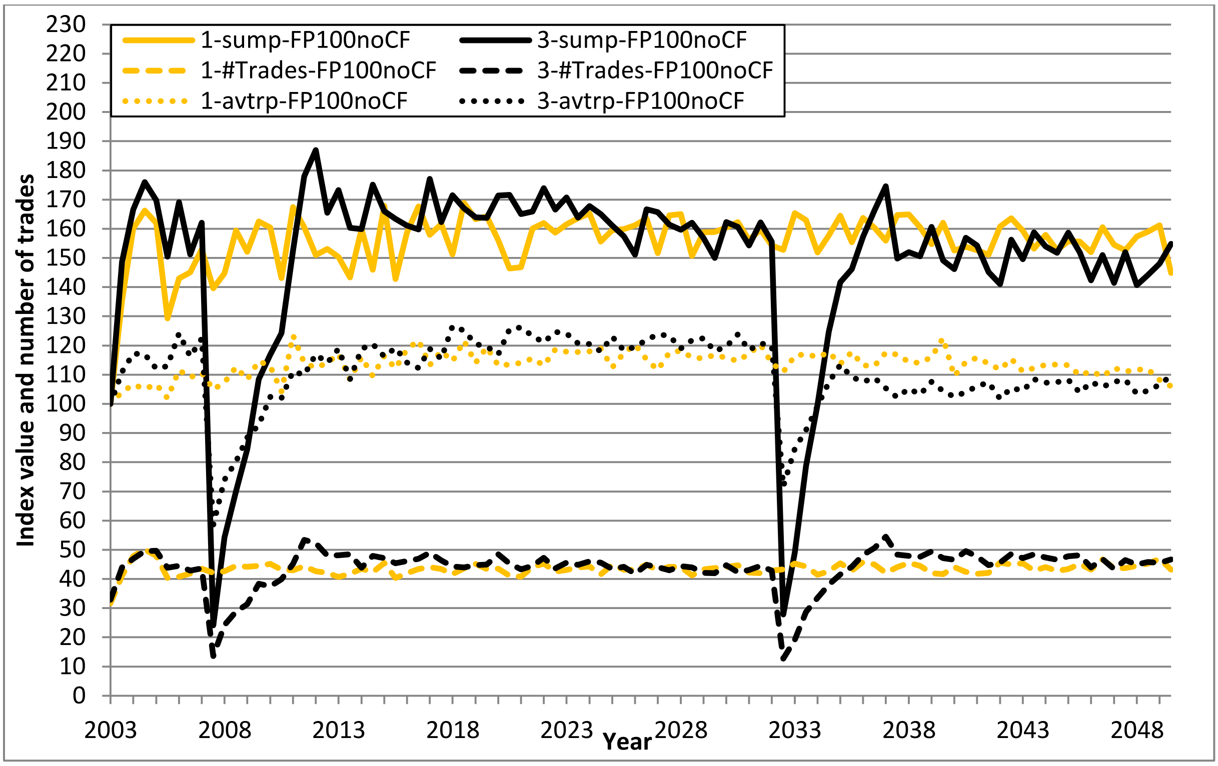

Figure 16: The Impact of risk perception bias on property values, in the current 100 year floodplain without the coastal front properties (FP100noCF), under current climate conditions. The following results are displayed for scenarios 1 and 3: sump - the total value of the trades in each time step for the FP100noCF zone, #Trades - the number of trades in each time step for the FP100noCF zone, and avtrp - the average trade price in each time step for the FP100noCF zone.

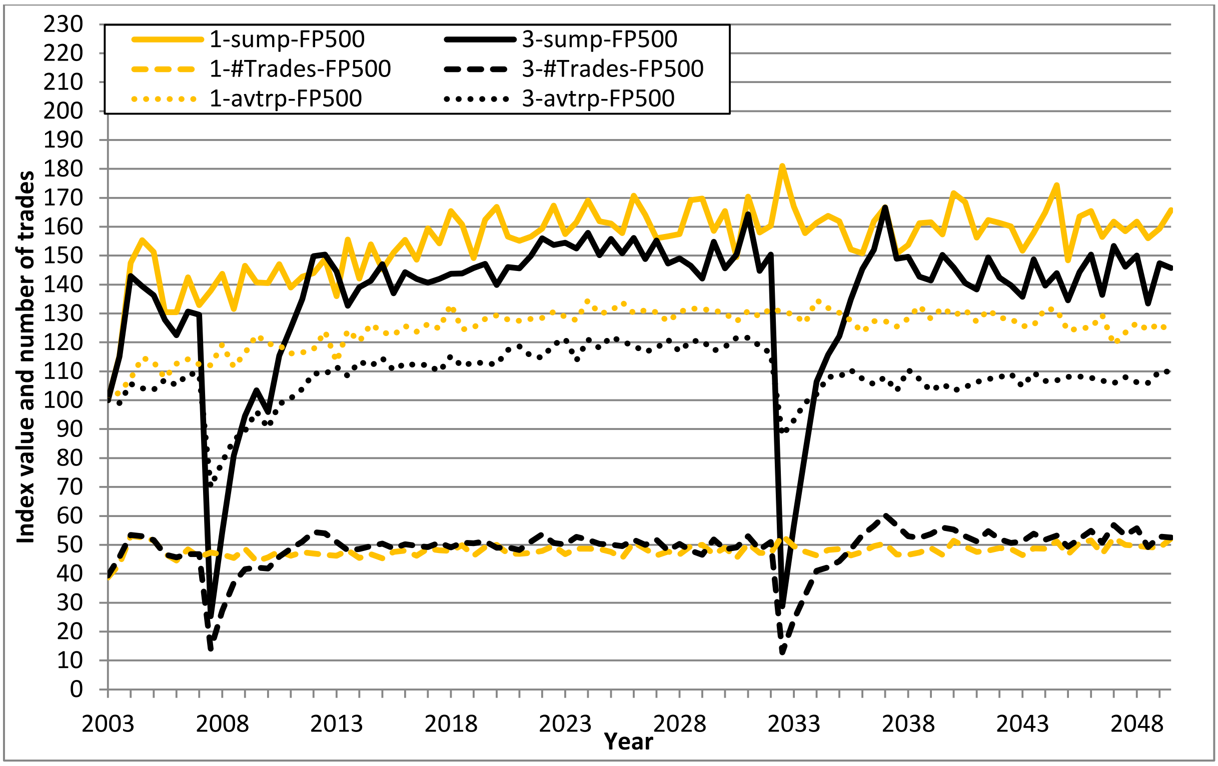

Figure 17: The Impact of risk perception bias on property values, in the current 500 year floodplain (FP500), under current climate conditions. The following results are displayed for scenarios 1 and 3: sump - the total value of the trades in each time step for the FP500 zone, #Trades - the number of trades in each time step for the FP500 zone, and avtrp - the average trade price in each time step for the FP500 zone.

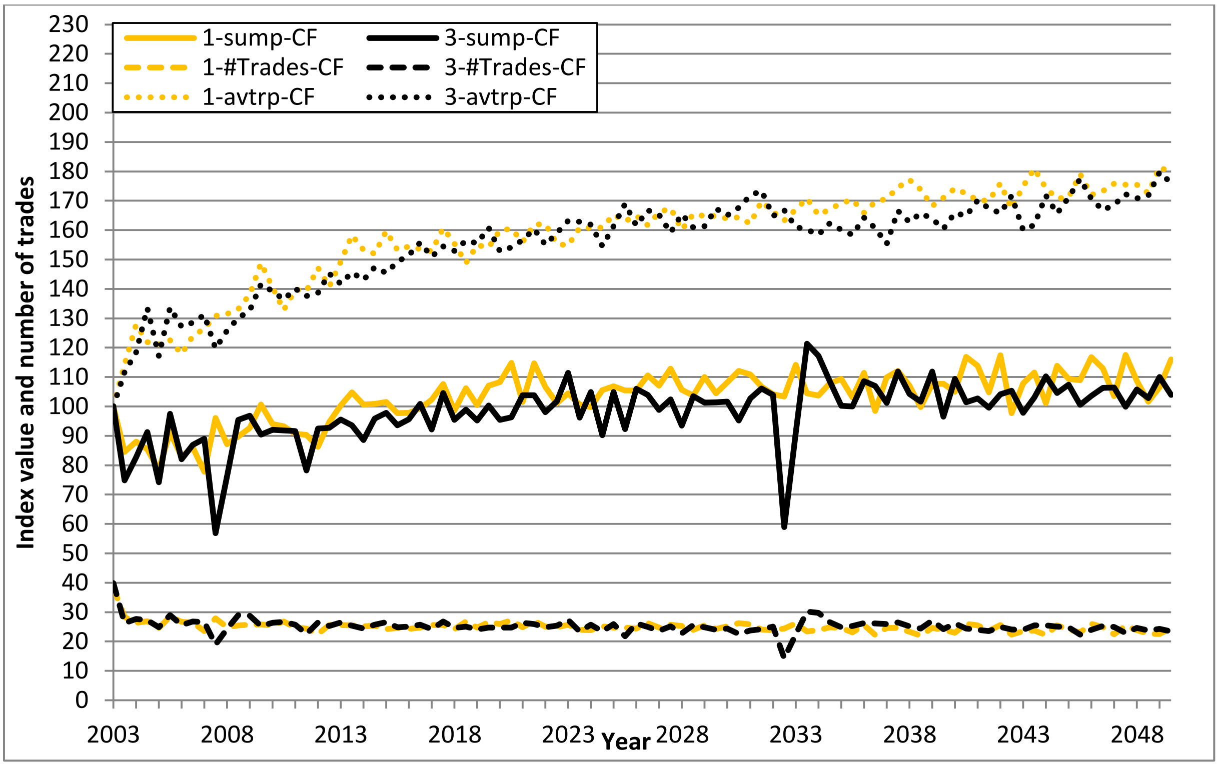

Figure 18: The Impact of risk perception bias on property values, for the coastal front properties (CF), under current climate conditions. The following results are displayed for scenarios 1 and 3: sump - the total value of the trades in each time step for the CF zone, #Trades - the number of trades in each time step for the CF zone, and avtrp - the average trade price in each time step for the CF zone.

5.2.3. The Impact of climate change on property values under risk perception bias

With both scenario 3 and 4 operating under risk perception bias (subjective risk) the results allow to visualize the effect of climate change with the influence of risk perception bias.

In Figure 19, as we did with scenarios 1 and 2, we see comparable levels of prices and trades for both scenarios, but this time with a slight increase in the number of trades under climate change conditions. Noticeable is the enormous spike in number of trades and trade volume during the aftermath of a flood event. Again the FP0 zone only calculates utilities for a no-flood situation (U_{NF} in equation 3), this leads to higher utility levels after flooding events compared to the flood-affected utility levels of all other properties and thus more properties being sold in this safe zone. Interesting to see is the small decline in the average property price after a flood event. This is due to the fact that even the cheaper houses in this zone have a higher utility value in the wake of a flood event than some houses in the flooded areas. The current 100 year flood zone (Figure 20) and the current 500 year flood zone (Figure 21), in contrast with the FP0 zone, show an enormous decrease in the number of trades and the total trade volumes. Even though the trade volumes are equal in the FP500 flood zone (Figure 21), under climate change conditions less houses are being sold but the houses being sold are more expensive. The difference in number of trade can also be seen in Figure 19 only in the opposite direction. In Figure 22 the coastal front properties show similar results as for scenarios 1 and 2, the only difference is noticeable in the drop in sales volume and the number of trades in the same year as a hurricane occurs. At the first time step following a flood event the risk perception bias (A-RPbias) equals 1, this means that for this time step the utility calculation will be solely based on the utility in case of flood (U_F equation 2).

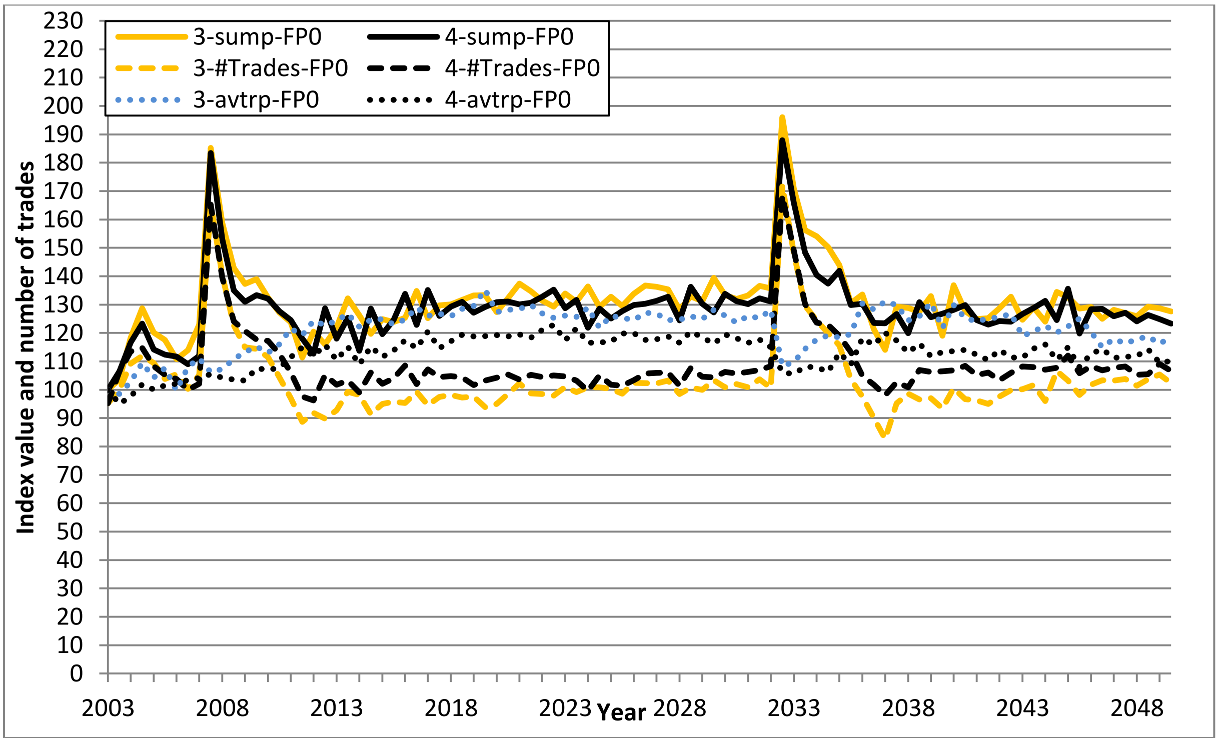

Figure 19: The impact of climate change on property values, in the safe zone (FP0), under risk perception bias. The following results are displayed for scenarios 3 and 4: sump - the total value of the trades in each time step for the FP0 zone, #Trades - the number of trades in each time step for the FP0 zone, and avtrp - the average trade price in each time step for the FP0 zone.

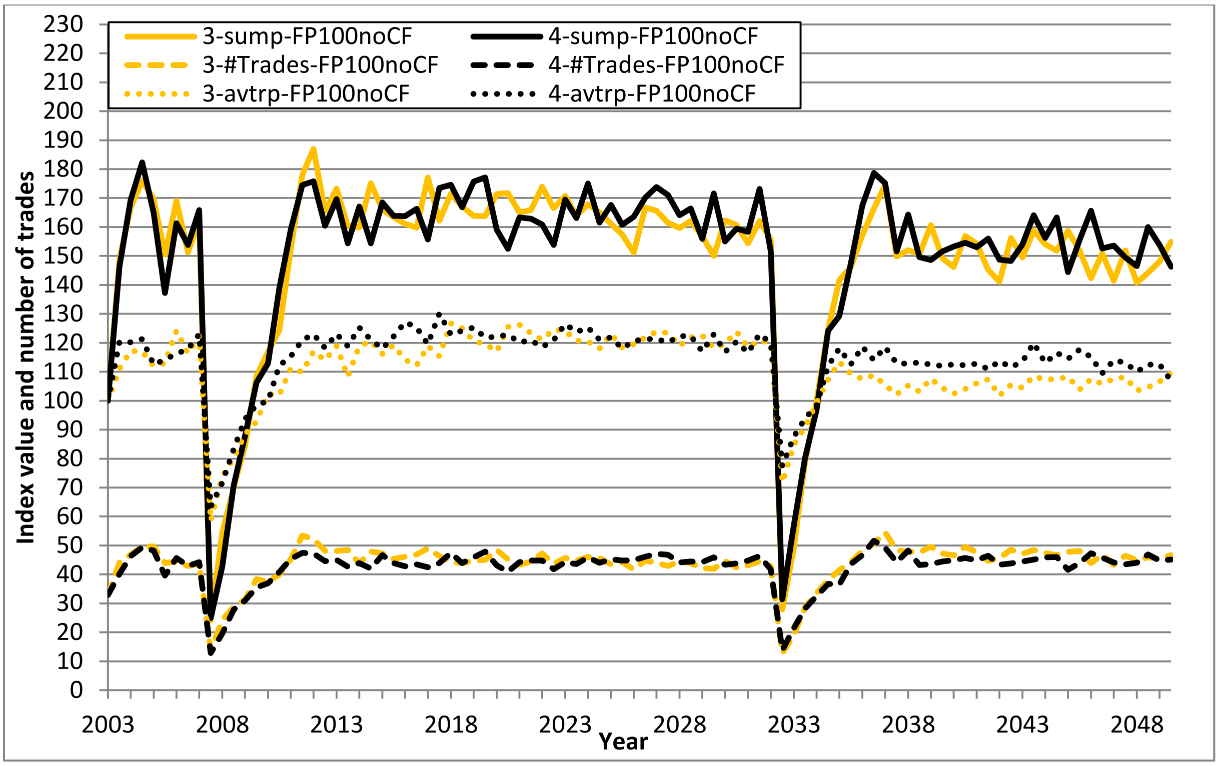

Figure 20: The impact of climate change on property values, in the current 100 year floodplain without the coastal front properties (FP100noCF), under risk perception bias. The following results are displayed for scenarios 3 and 4: sump - the total value of the trades in each time step for the FP100noCF zone, #Trades - the number of trades in each time step for the FP100noCF zone, and avtrp - the average trade price in each time step for the FP100noCF zone.

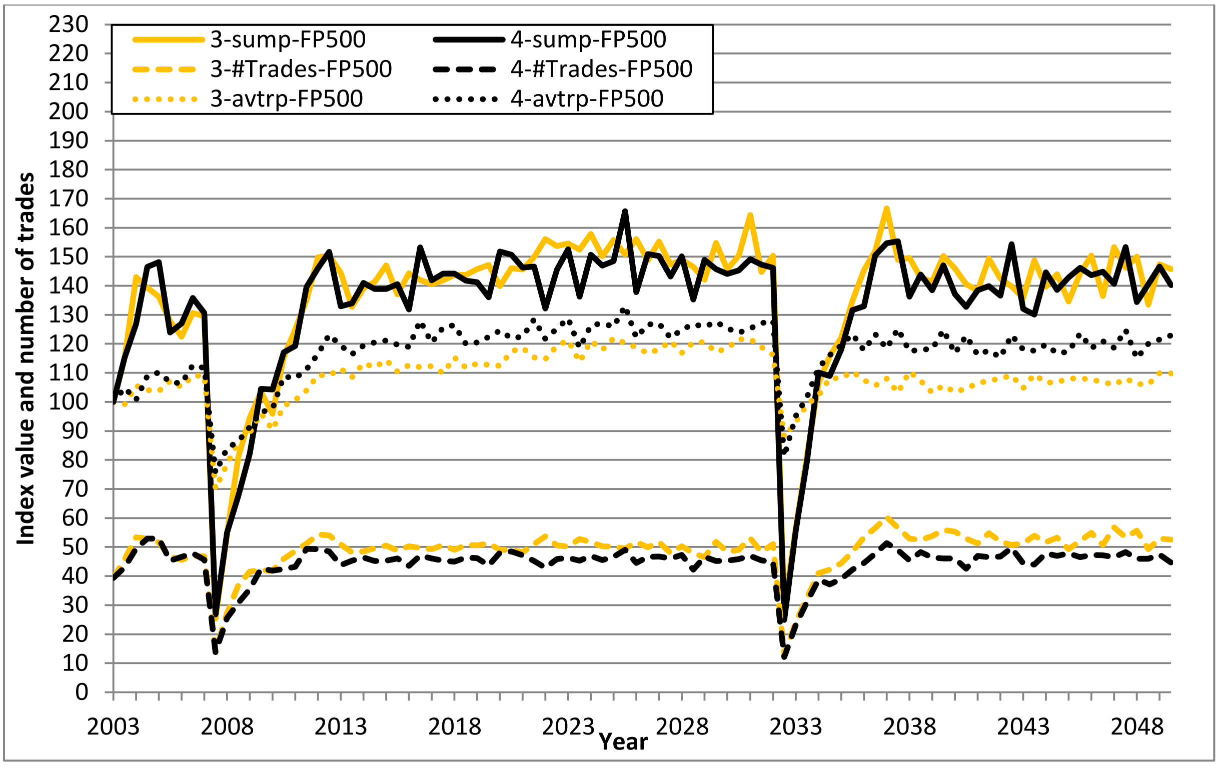

Figure 21: The impact of climate change on property values, in the current 500 year floodplain (FP500), under risk perception bias. The following results are displayed for scenarios 3 and 4: sump - the total value of the trades in each time step for the FP500 zone, #Trades - the number of trades in each time step for the FP500 zone, and avtrp - the average trade price in each time step for the FP500 zone.

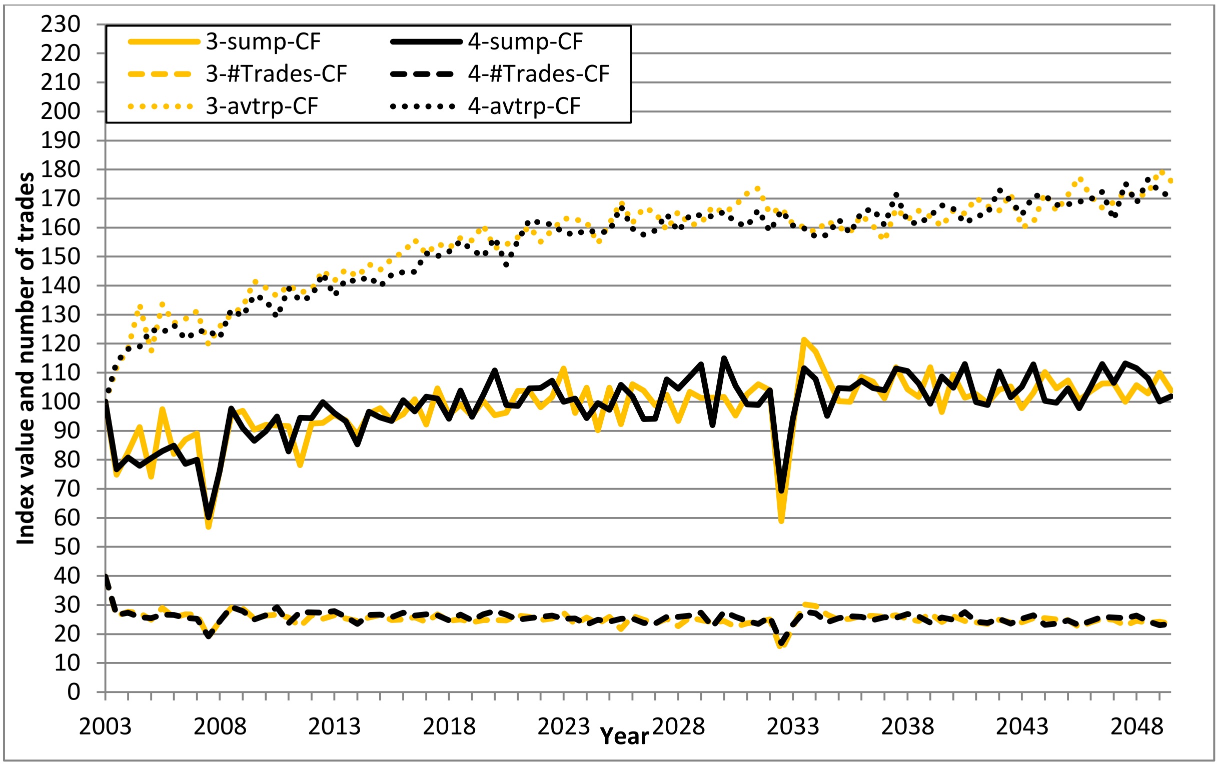

Figure 22: The impact of climate change on property values, for the coastal front properties (CF), under risk perception bias. The following results are displayed for scenarios 3 and 4: sump - the total value of the trades in each time step for the CF zone, #Trades - the number of trades in each time step for the CF zone, and avtrp - the average trade price in each time step for the CF zone.

5.2.4. The Impact of climate change and risk perception bias on property values

In order to determine the combined effects of climate change and risk perception bias, scenarios 1 and 4 are compared. With scenario 1 operating under perfect information (objective risk) and steady state climatic conditions, and scenario 4 operating under risk perception bias (subjective risk) and climate change conditions, the results allow to visualize the effects of both climate change and risk perception bias.

The FP0 zone in Figure 23 shows little difference between the number of trades (+/- 5) for scenarios 1 and 4. For the average trade price and the total trade volume a difference of 10 percentage points exists, in favor of scenario 1. Because scenario 4 operates under subjective risk, the FP0 zone under scenario 4 becomes less desirable since it has less access to e.g. coastal amenities, lowering the utility value and property value, which are available in the FP100noCF zone (Figure 24), leading to a higher average utility. The explanation offered for the observed trends in the FP0 zone can also be given for the FP500 flood zone (Figure 25). However, even though the average trade price for scenario 4 is on average 12% lower, the trade volume is on average 17% lower. This would suggest that the share of expensive properties sold in scenario 4 is higher than for scenario 1. Figure 26 again shows very little difference between the two scenarios in the CF zone except for the drop in trade volume on the time step of the flooding events. This is consistent across all scenarios and all the comparisons made previously.

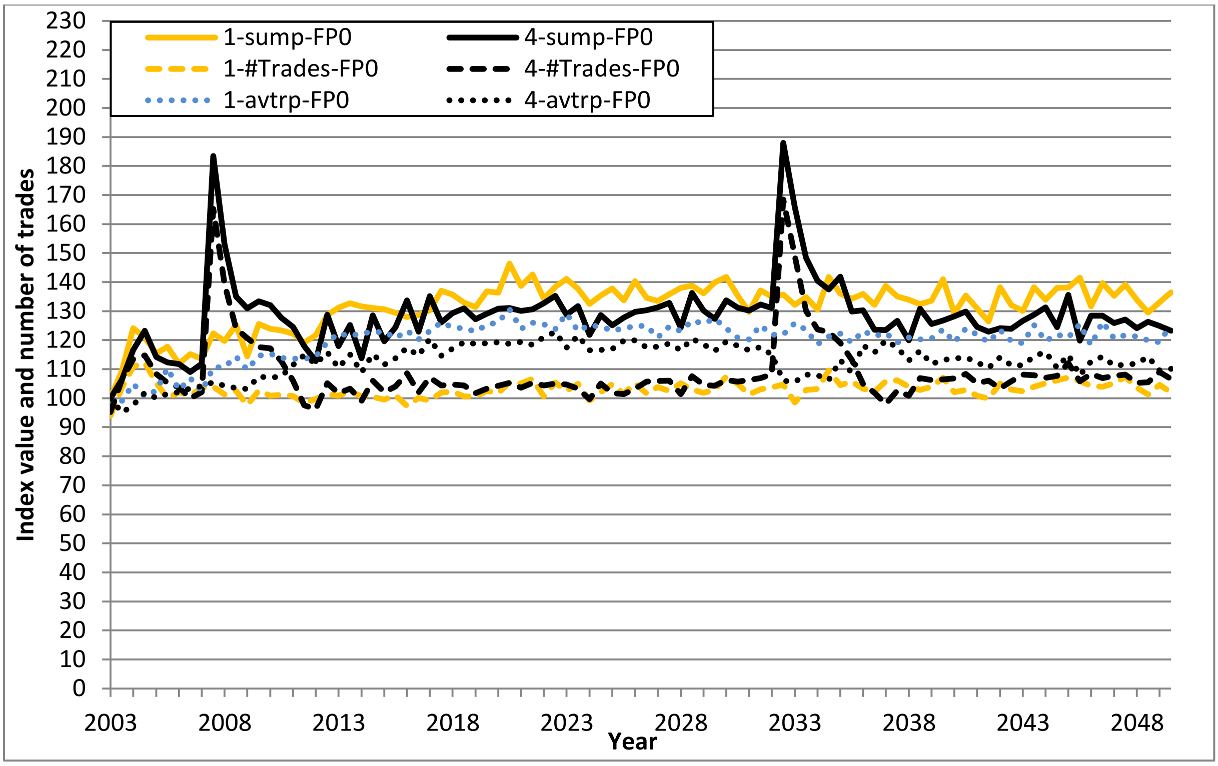

Figure 23: The impact of climate change and risk perception bias on property values, in the safe zone (FP0). The following results are displayed for scenarios 1 and 4: sump - the total value of the trades in each time step for the FP0 zone, #Trades - the number of trades in each time step for the FP0 zone, and avtrp - the average trade price in each time step for the FP0 zone.

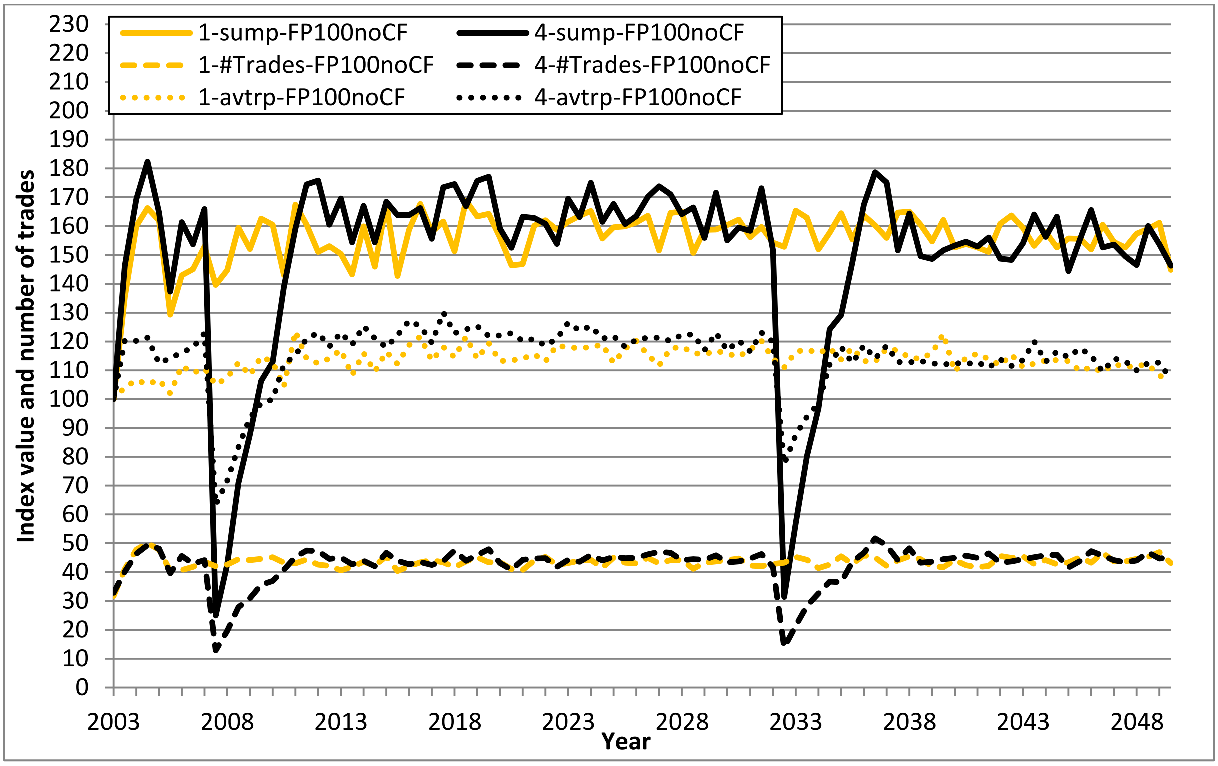

Figure 24: The impact of climate change and risk perception bias on property values, in the current 100 year floodplain without the coastal front properties (FP100noCF). The following results are displayed for scenarios 1 and 4: sump - the total value of the trades in each time step for the FP100noCF zone, #Trades - the number of trades in each time step for the FP100noCF zone, and avtrp - the average trade price in each time step for the FP100noCF zone.

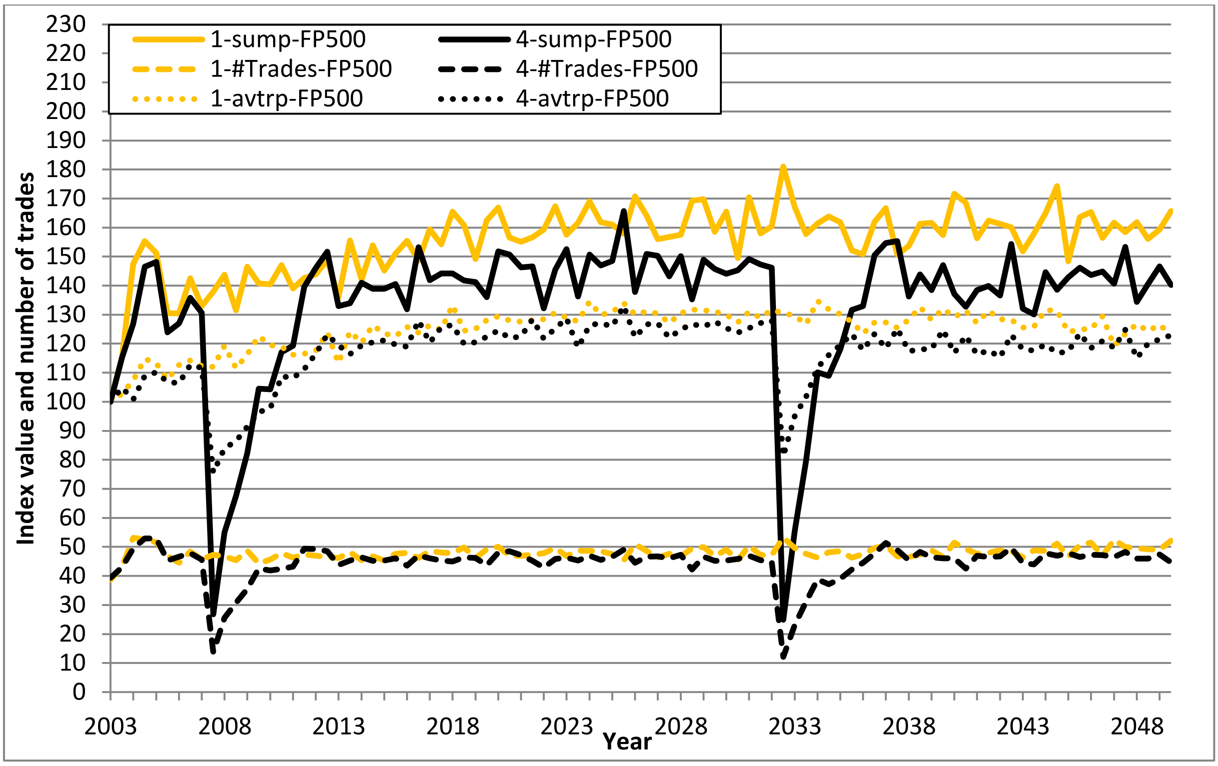

Figure 25: The impact of climate change and risk perception bias on property values, in the current 500 year floodplain (FP500). The following results are displayed for scenarios 1 and 4: sump - the total value of the trades in each time step for the FP500 zone, #Trades - the number of trades in each time step for the FP500 zone, and avtrp - the average trade price in each time step for the FP500 zone.

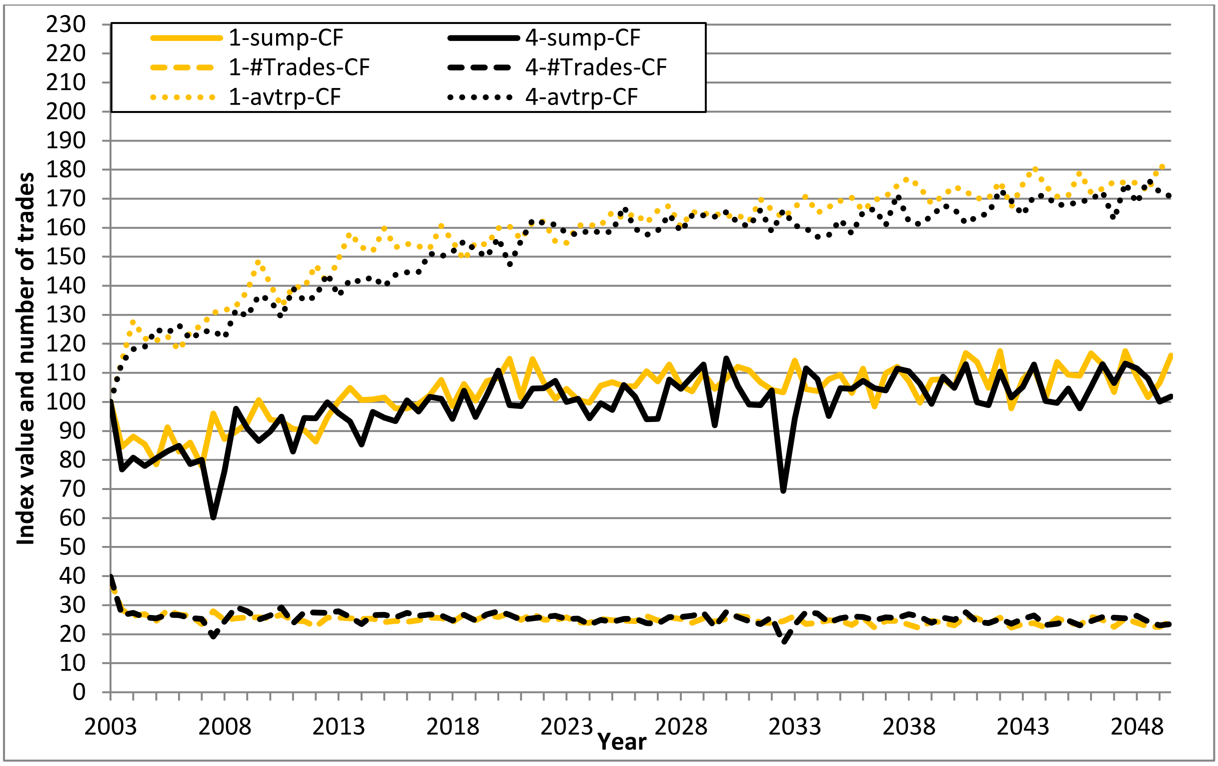

Figure 26: The impact of climate change and risk perception bias on property values, for the coastal front properties (CF). The following results are displayed for scenarios 1 and 4: sump - the total value of the trades in each time step for the CF zone, #Trades - the number of trades in each time step for the CF zone, and avtrp - the average trade price in each time step for the CF zone.

5.2.5. Results overview

In this section an overview of the simulation results is presented (Table 9). The results are divided by flood zone and show the mean and the standard deviation from the last 5 years in the simulation.

Table 9: Results overview divided by flood zone, each showing the results for all 4 scenarios. The mean and standard deviation for the total trade volume, average trade price, and the number of trades are shown. The mean and standard deviation for the total trade volume and the average trade price are indexed values. The starting values for the total trade volume and average trade price are shown as well, these have the index value 100.

Safe zone (FP0)								
	Total trade volume (sump)			Average trade price (avtrp)			Number of trades (#Trades)	
	Starting value (in dollars)	μ	σ	Starting value (in dollars)	μ	σ	μ	σ
Scenario 1	21,248,819	136	3.6	226,559	122	2.7	105	1.9
Scenario 2	20,896,569	143	5.8	221,642	129	2.9	105	2.7
Scenario 3	21,461,325	128	2.0	225,910	119	2.9	103	1.8
Scenario 4	21,461,325	126	3.9	225,910	112	2.1	108	1.9
Current 100 year flood zone (FP100noCF)								
	Total trade volume (sump)			Average trade price (avtrp)			Number of trades (#Trades)	
	Starting value (in dollars)	μ	σ	Starting value (in dollars)	μ	σ	μ	σ
Scenario 1	6,499,556	155	4.6	205,907	110	2.0	45	1.3
Scenario 2	5,981,875	180	9.5	196,076	130	4.0	43	1.6
Scenario 3	6,285,244	149	5.8	191,185	107	1.9	46	1.5
Scenario 4	6,285,244	153	6.2	191,185	113	2.9	45	1.6
Current 500 year flood zone (FP500)								
	Total trade volume (sump)			Average trade price (avtrp)			Number of trades (#Trades)	
	Starting value (in dollars)	μ	σ	Starting value (in dollars)	μ	σ	μ	σ
Scenario 1	5,958,575	160	5.0	154,285	125	2.6	50	1.9
Scenario 2	5,858,500	172	6.9	151,291	148	2.0	45	1.6
Scenario 3	6,276,956	144	6.6	159,687	108	1.4	53	2.4
Scenario 4	6,276,956	143	4.8	159,687	113	2.9	47	1.0
Coastal front properties (CF)								
	Total trade volume (sump)			Average trade price (avtrp)			Number of trades (#Trades)	
	Starting value (in dollars)	μ	σ	Starting value (in dollars)	μ	σ	μ	σ
Scenario 1	15,101,175	110	5.3	396,450	176	3.3	24	1.2
Scenario 2	15,086,719	114	4.0	391,381	187	2.5	24	0.9
Scenario 3	15,643,069	105	3.0	395,824	173	3.8	24	0.9
Scenario 4	15,643,069	106	5.1	395,824	171	3.8	25	1.1

6. Discussion

In this chapter the results of this study will be evaluated and discussed. First, the model sensitivity will be discussed to determine the robustness of the simulation results. Second, the relation between storm intensity and storm surge level, as well as the influence of barrier islands on the surge levels will be discussed. Third, a case is made to allow hurricane wind damage to start the risk perception bias procedure. And finally, a short discussion will also be held about the effect of decreasing the succession time of flood events and the fixed value characteristics of coastal front properties.

6.1. Model sensitivity

With this sensitivity analysis the sensitivity of the model to the input parameters will be determined. These results will be compared to the sensitivity of the model to the four scenarios described in chapter 5, to determine the robustness of the scenario results. The parameters to be used in the sensitivity analysis can be found in Table 10. Four parameters were not included in this sensitivity analysis: the preference for spatial goods over composite goods (prefAlfa), the preference for environmental amenities (prefGamma), the average budget for households (avBudget) and thestandard deviation of budgets (budgetStDev). The values for prefAlfa and prefGamma are set in accordance with the suggested values from Wu & Plantinga (2003) and Wu (2006). The budgets are set empirically according to the U.S. statistics data for household incomes in Carteret county and therefore do not require avBudget and budgetStDev.

Table 10: Input parameters from the RHEA model used in the sensitivity analysis. *Years of mortgage and N of cells both are input parameters which require an integer as value, therefore for these parameters it is not possible to adhere to the same distribution as is used for the other input parameters.

Input parameter	0.90 * Base Variable	0.95 * Base Variable	Base variable	1.05 * Base Variable	1.10 * Base Variable
Fraction_on_sale; determines the share of owners who decide to become sellers	0.126	0.133	0.14	0.147	0.154
newBuyerCoef; determines how many of the newcomers to the area become buyers	0.63	0.665	0.7	0.735	0.77
aDelta; Difference between bid and ask price, which buyer/seller is ready to accept in price negotiations	0.9	0.95	1	1.05	1.10
Gsd; standard deviation for prefGamma	0.045	0.0475	0.05	0.0525	0.055
Travel cost multiplier	0.9	0.95	1	1.05	1.1
Years of mortgage*	27	29	30	31	33
N of cells*	3	4	5	6	7

A reference simulation is required to analyze the sensitivity of the model. The settings for the input parameters used in this reference simulation can be found in Table 13, appendix C2. Every simulation consists of only a single input parameter being changed in comparison to the reference simulation and is run for a total of 10 time steps (i.e. 5 years).

The total property value from the reference simulation is compared to total property values of any of the sensitivity analysis runs to determine the sensitivity of the model to that particular parameter. The sensitivity of the model to its input parameters can be seen in Figure 27. The variation in total property value of the four scenarios lies between -1.0 and -2.8 percent of the reference simulation, which lies within the range of most parameters in the sensitivity analysis.

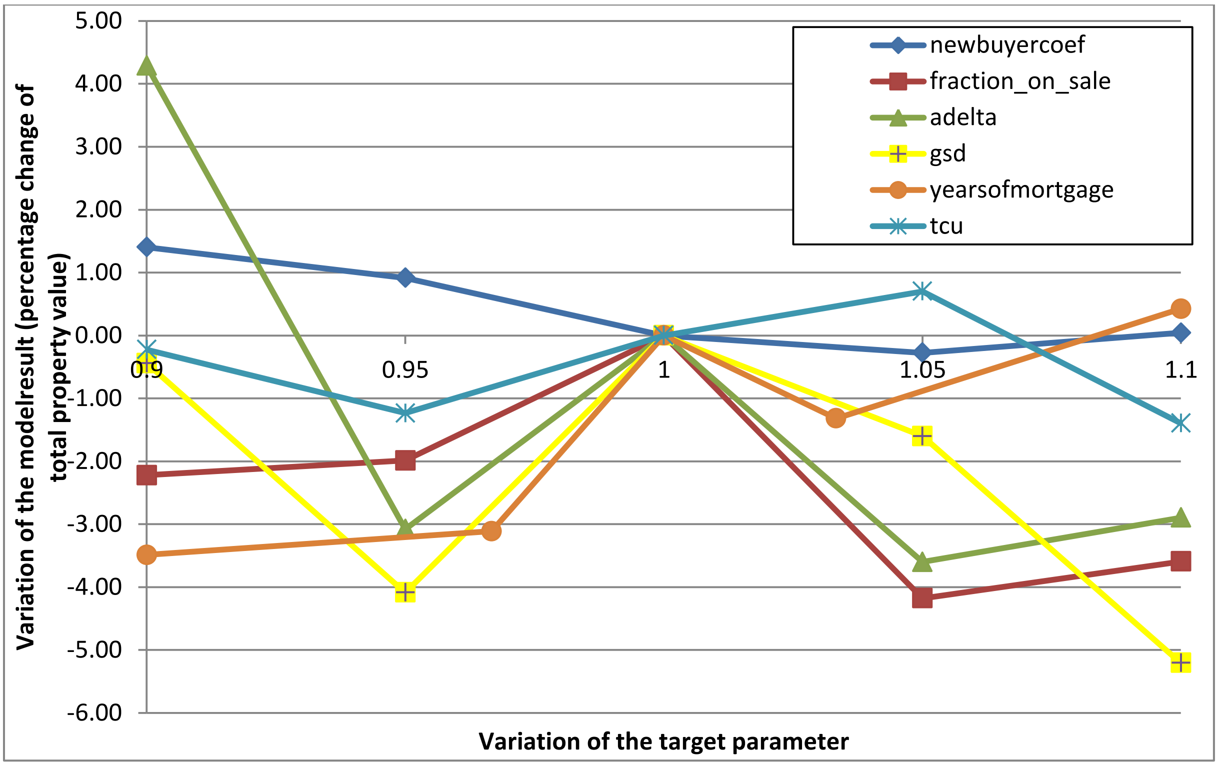

Figure 27: The result of the sensitivity analysis for the input parameters described in Table 10.

6.2. Barrier islands

The North Carolina coast is protected by a series of barrier islands. These barrier islands protect the back-barrier estuary, at which Beaufort is situated, from the extremely high-energy oceanic conditions (Riggs & Ames, 2003) such as hurricane storm surges. In Figure 2 it can be seen that the barrier islands around Beaufort are quite susceptible to erosion, around 2 meters per year (N.C. Division of Coastal Management, 2014). Under climate change conditions higher sea levels and heavier storms will speed up the rate of erosion, potentially putting the back-barrier estuary at an increased level of risk.

If the barrier islands capacity to protect the back-barrier estuary from high-energy oceanic conditions decreases, the coastal front properties will be at an increased risk from high-energy oceanic conditions. This could possibly decrease coastal front property values as damages to the properties occur more often. In chapter 5.2 we have seen that coastal front properties have a stable property value across the four scenarios due to the high level of amenities these properties have. With increasing property damages the coastal front properties high level of amenities might no longer be enough to keep buyers interested in the properties, leading to decreasing property values.

6.3. Storm surge

During this research, the assumption has been made that a once in a 100 years storm generates a once in 100 years storm surge and thus is responsible for a once in a 100 years flood event. However, even though the storm intensity is the primary contributor to storm surge levels, there are many factors influencing storm surge levels. These factors include the central pressure, the size of the storm, the storm forward speed, the angle of approach to the coast, the shape of the coastline, the width and slope of the ocean bottom, and the local features of a coastline (NOAA National Hurricane Center, 2008).

A hurricane with high wind speeds will not always cause a large storm surge level, such as a hurricane with low wind speeds will not always cause a small storm surge level. Hurricane Katrina, a category 3 hurricane at landfall, was responsible for catastrophic damage with a 8.5 meter storm surge. Hurricane Ike, a category 2 hurricane at landfall in Texas, was accompanied by a 6 meter storm surge. Hurricane Charley, a category 4 hurricane at landfall in Florida, produced a storm surge of 2 meters. Hurricane Irene, only a category 1 at landfall in North Carolina, had a storm surge of 3 meters, high enough to flood the 500 year flood zone in certain areas (NOAA National Hurricane Center, 2008).

The storm surge level does not solely depend on storm intensity, but also on a variety of other factors. The flooding probabilities calculated in chapter 3.4.2 do rely solely on the storm intensity and might thus not accurately depict the flooding probabilities for the future. The flooding probabilities might be higher or lower than what has been calculated in chapter 3.4.2 and might affect the property values positively or negatively.

6.4. Hurricane winds

Currently the model only runs the risk perception bias procedure for a flooding caused by a category 4 or 5 hurricane (section 3.4.2). From section 6.3 it becomes clear that a large hurricane is not necessarily accompanied by a storm surge level capable of causing a flood event. But even though a category 4 or 5 hurricane might not cause a flood event due to the lack of a sufficiently large storm surge, the wind speeds associated with these hurricanes might do just as much damage. Conversely, in the current model category 3 hurricanes (still considered major hurricanes) do not cause a flooding but high wind speeds are still capable of causing devastating damage. Category 1 and 2 hurricanes will cause some to extensive damage due to hurricane winds.

The Saffir-Simpson hurricane wind scale rates the hurricanes into the five known categories and estimates the potential for property damages. A category 3 or higher is rated as a major hurricane because of the significant potential for damages and loss of life. The major hurricanes are rated as follows on the Saffir-Simpson hurricane scale:

Category 3 - Devastating damage will occur: Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes (Schott et al., 2012).

Category 4 - Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months (Schott et al., 2012).

Category 5 - Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months (Schott et al., 2012).

Considering the devastation hurricane winds can cause, it is justifiable to start the risk perception bias procedure even if a flooding event does not occur (per section 6.4), questions arise for which categories of hurricanes this should be applied and if the Logarithmic discount coefficient curve from Figure 10 would still be applicable.

6.5. Housing market response to myopia and amnesia

Figure 9 shows the housing market response to myopia and amnesia relevant to this research. The current limited amount of flooding events the model operates under allow for ample time for houses to return to the zero risk constant quality house price (Figure 9). However, if sections 6.3 and 6.4 are considered, climate change could lead to an increase in catastrophic events which start the risk perception bias procedure. This would diminish the available time for houses to return to the zero risk constant quality house price, perhaps so drastically that a situation is created in which not enough time can pass for the zero risk constant quality house price to be reached. This situation is shown in Figure 28 and would lead to a declining risk-adjusted constant quality house price.

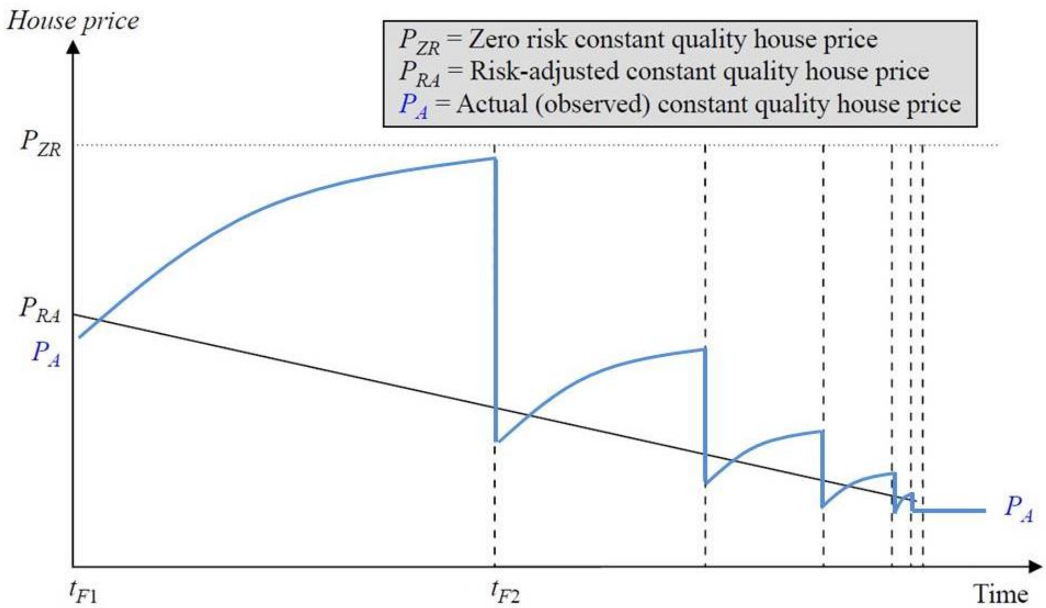

Figure 28: House prices with amnesia and myopia under frequent flooding (updated from Pryce et al., 2011)

6.6. Coastal front properties

Each property has a certain value for coastal amenities, depending on how far the property is situated from the coast line. The closer a property is to the coast line, the higher this value is. The RHEA model makes an extra calculation when calculating the utility value (chapter 2.2, equations 1,2,3) for a coastal front property. The RHEA model multiplies the already high value for coastal amenities by a factor of ten, increasing the utility value for a coastal property immensely. If Figure 14, Figure 18, Figure 22, and Figure 26 are considered, it should be noticed that these properties retain their value, regardless of objective risk and only seem to be affected if the subjective risk bias reaches a value of 1 (when the utility calculation is based only on equation 2).

Even though it would be realistic to assume that coastal front properties have a higher amenity value compared to non-coastal front properties, the current level of a tenfold increase in amenity value seems too high. Under the current amenity levels the coastal front properties are virtually unaffected by either climate change or the risk perception bias, even though the coastal front properties are the most affected by flooding. Lowering the amenity values for coastal front properties would most likely lead to these properties being influenced more by climate change and risk perception bias, and lead to lower property values compared to the current results from the four scenarios.

6.7. Flooding probabilities

The flooding probabilities determined in section 3.4.2 are expected to be reached mid-21st century and are predicted to rise even further towards the end of the 21st century. By 2100 the current 100 year storm is predicted to be a 43 year storm. The current 500 year storm is by 2100 a 131 year storm (Figure 29).

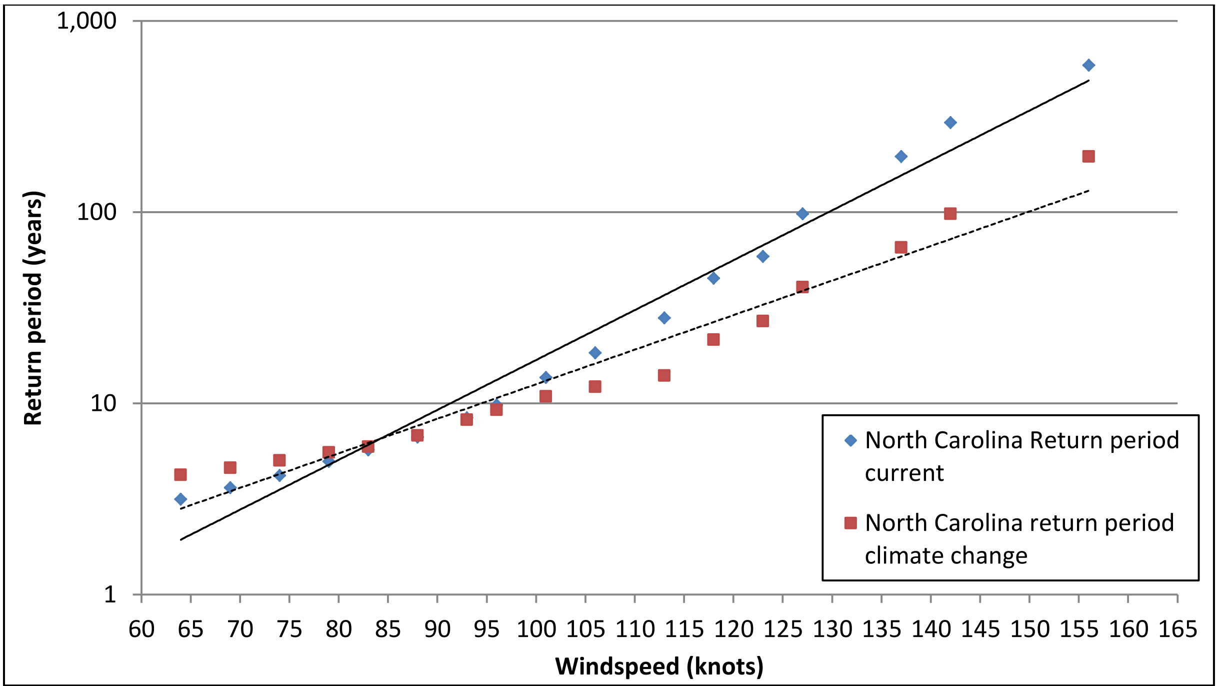

Figure 29: North Carolina hurricane return period. Wind speed plotted against the return period. Calculation for the current return period (blue data points) can be found in chapter 3.4.1, calculation for the future return period (the year 2100) (red data points) similar to the calculation in chapter 3.4.2.

The flooding probabilities for 2050 were used for the entire 47 year simulation (2003-2050) when in fact it would have been more realistic to have them increase during the simulation. This would most likely lead to the results diverging from each other as the years progress from 2003 to 2050, with the results being similar at the start of the simulation and reaching the greatest divergence at the end of the simulation.

6.8. Flood events

In the current simulation a flood event triggers the risk perception bias procedure for traders in both the current 100 and 500 year flood zones. Traders who trade in the FP0 zone are unaffected, since the zone they are in will not flood. For all intents and purposes the two simulated flood events are 500 or 231 year (under climate change conditions) events. Even though it is possible for two 500 year events occurring within 30 years of each other it is very improbable. The reason to simulate both these events as 500 year floods has been to determine the effect of risk perception bias for the traders in both the current 100 and 500 year flood zones.

The composition of the two flood events will most likely influence the outcome of this study. Had one of the two flood events been a 100 year flood event instead of 500 year flood event we would probably have seen properties in the 500 year floodplain become more desirable compared to the current simulation. This would especially be true during a 100 year flood event and the following 5 years in which it might become the superior alternative much in the same way as the FP0 zone currently functions. This might even be more obvious if both simulated flood events become 100 year flood events, in this case the current 500 year flood zone might act in the same way the FP0 zone currently functions.

7. Conclusions and recommendations

In this chapter, answers to the research questions will be presented to be able to achieve the research objective set at the beginning. *“To quantify the impacts of climate change, and the effect of the associated flood risks and risk perception bias on coastal urban property values at the North Carolina coastal zone.”* Once the research questions are answered recommendations will be made for future research.

7.1. Conclusions

In order to achieve the research objective, three sub research question were formulated in chapter 1. The answer to each of these research questions has contributed to achieving the research objective.

The first research question “*To what extent will future climate change affect flood risks of the North Carolina coastal zone?”*, was answered in chapter 3. This chapter saw that for the year 2050 the flooding probability for the North Carolina coastal zone will change drastically. Since hurricanes are the dominant cause of coastal flooding this change is driven by the change in hurricane frequencies. Sea level rise has been disregarded in determining coastal flooding, this was mainly due to the limited amount of sea level rise for the year 2050. The current 100 year storm will have a return period of 61 years by 2050 and the current 500 year storm will be more than twice as likely to occur in 2050 with a decreased return period of 231 years.

Research question number two “*How can (changes to) future flood risks and risk perception bias be simulated for the North Carolina coastal zone under variable climate change scenarios?*, was answered in chapter 4. This chapter made the distinction between objective risk, the actual flooding probabilities to be used under perfect information scenarios and subjective risk, the flooding probabilities which traders had to be used under risk perception bias scenarios. The subjective flooding probabilities are a dynamic process which is started by a flood event. The risk perception bias will be highest directly after a flood event and will take five years to dissipate allowing the bias to return to normal levels.

The final research question, research question number three “*What is the impact of coastal flood risk changes and risk perception bias on coastal property values at the North Carolina coastal zone?”*, was answered in chapter 5 and is summarized below.

Flood zone FP0: The total trade volumes simulated for 2050 under perfect information (i.e. objective risk) are 1.3 to 1.4 times their starting value in 2003. Under risk perception bias these values drop slightly to 1.2 to 1.3 times the starting value. The combined impacts of climate change and risk perception bias lead to an average decrease in total trade volume of 10 percent, and a 10 percent decrease in the average trade price when compared to the base simulation.

Flood zone FP100noCF: The total trades volumes reached by the end of the simulation under perfect information are 1.5 to 1.9 times their starting value. Under risk perception bias these values are the same, around 1.5 times their starting value. The combined impacts of climate change and risk perception bias leads to a negligible decrease in total trade volume, and a small increase in average trade price of 3 percent for 2050.

Flood zone FP500: The total trades volumes reached by the end of the simulation under perfect information are 1.6 to 1.8 times their starting value. Under risk perception bias these values drop to 1.4 times the starting value. The combined impacts of climate change and risk perception bias lead to an average decrease in total trade volume of 17 percent and average trade price of 12 percent for 2050 when compared to the base simulation. With the number of trades being stable this means that property values in the FP500 flood zone are the most negatively affected by the combined impacts of climate change and risk perception bias.

Flood zone CF: The combined impacts of climate change and risk perception bias are relatively small in comparison to the other zones. The coastal front properties are relative fixed value properties across the four scenarios with the total trade volume 4 percent lower for scenario 4 compared to scenario 1. The average trade price across the four scenarios varies between 1.7 to 1.9 times the starting value.

With the three research questions answered we have been able to achieve the research objective.

"To quantify the impacts of climate change, and the effect of the associated flood risks and risk perception bias on coastal urban property values at the North Carolina coastal zone."

In conclusion, across all four flood zones we see that scenario 2 has the highest overall trade volume and the highest average trade price. This can be attributed to traders compensating the loss of utility value due to increased flooding probabilities by purchasing homes with a higher utility value. Since these properties cost more it increases both the total trade value and the average trade price. Scenario 2 operates under climate change conditions and perfect information, for scenario 4 the objective flooding probabilities are replaced with subjective probabilities. This has a drastic effect as the difference in trade volume and trade price between scenario 2 and 4 reaches levels up to 30 percent.

When comparing scenario 4 with the base simulation we can still see this difference, however, on a smaller scale. The FP500 zone is the most negatively affected by the impacts of climate change and risk perception bias with the total trade volume and average trade price dropping as much as 20 percent. The FP0 zone is affected approximately half as much by the impacts of climate change and risk perception bias with the total trade volume and average trade price dropping with 10 percent. The FP100noCF and CF zone are both showing to be minimally affected by the impacts of climate change and risk perception bias with the total trade volume and average trade price dropping between the 2 and 5 percent. The values for the CF zone properties are constant throughout all four scenarios, being relatively unaffected by either climate change or risk perception bias and seems to be a safe investment monetary wise.

7.2. Recommendations

In this section recommendations will be made for future research, these recommendations are based on discussion points raised in chapter 6.

The first part of these recommendations will pertain to the events that can start the risk perception bias procedure. Currently, the risk perception bias procedure will only be started during flooding events caused by sufficiently large hurricanes. Sections 6.3 and 6.4 showed that it might be valid to have the risk perception bias procedure be started by other events as well. Therefore I would suggest to research storm surge levels for hurricanes affecting the North Carolina coastal zone.

With this new information about storm surge levels I would recommend to add a digital elevation map to the RHEA model. Combining elevations of properties with the elevation of storm surge levels would allow for accurate tracking of the flooding a hurricane might cause, as well as to assess the damage to properties based on the inundation depth.

As was made clear in section 6.4, a hurricane can cause devastation even if it doesn't cause a flood. Even under the current RHEA model it would make sense to have the utility calculation for the FP0 flood zone consist of the two following parts; U_{WD}, utility in case of wind damage and U_{NWD}, utility in case of no wind damage. The two hurricanes currently responsible for starting the risk perception bias procedure are very strong hurricanes and would certainly impact the FP0 flood zone heavily, even without flooding this zone. From the storm surge research we might also learn that large hurricanes not necessarily produce large storm surges, however, large hurricanes due produce high wind speeds. This might lead to the risk perception bias procedure, for all the different zones, being started by a sufficiently large hurricane with an insufficiently large storm surge which.

Currently, the barrier islands protecting Carteret County are left out of the scope of this research even though they protect the back-barrier estuary, at which Beaufort is situated, from the extremely high-energy oceanic conditions. It would be interesting to know what level of protection the barrier islands offer and how the barrier islands evolve under climate change conditions.

The second part of my recommendations focusses on the risk perception bias itself and its simulation. Currently, the logarithmic discount coefficient curve from Figure 10, used in this research is logarithmic because it was considered the best option by (Bin & Landry, 2013). However, the way the perception changes over time is not considered and just assumed to be logarithmic.

An important consideration involving amnesia is the difference between individual amnesia and market amnesia. Even though individual households might be perfectly aware of flood risks, potential buyers coming from outside the area may not be. This causes information asymmetry, it would be beneficial to see how information asymmetry influences the property values.

Finally, the current research involved climate change conditions in accordance with mid-century conditions (2050). As climate change impacts are expected to increase exponentially, it would be interesting to study how property prices will react to climate change conditions at the end of the 21st century?

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Appendices

Appendix A Climate change

Appendix A accompanies chapter 3 and provides background information on the representative concentration pathways scenarios and the predicted global temperature change under these scenarios.

A1 The four representative concentration pathways scenarios

The four RCP scenarios are identified by the 21st century peak or stabilization value after 2100 of the Radiative Forcing (RF, in W/m^2). The lowest RCP scenario, RCP 2.6 (which is also referred to as RCP3][PD) peaks at 3 W/m^2 around the year 2050 and declines to 2.6 W/m^2 at the end of the 21st century. RCP 4.5 the medium low scenario and RCP 6.0 the medium high scenario, stabilize after 2100 at 4.2 and 6.0 W/m^2 respectively. RCP 8.5, the highest scenario reaches a forcing of 8.3 W/m^2 by 2100 but rises even further during the 22nd century (Collins et al., 2013). Figure 30 shows the historical and projected total anthropogenic RF between 1950 and 2100. Previous IPCC assessments (SAR IS92a, TAR/AR4 SRES A1B, A2 and B1) are compared with RCP scenarios. The total RF of the three families of scenarios (IS92, SRES and RCP) differ, for example for the year 2000, resulting from the knowledge about the emissions assumed having changed since the Third Assessment Report (TAR) and AR4 (Cubasch et al., 2013).

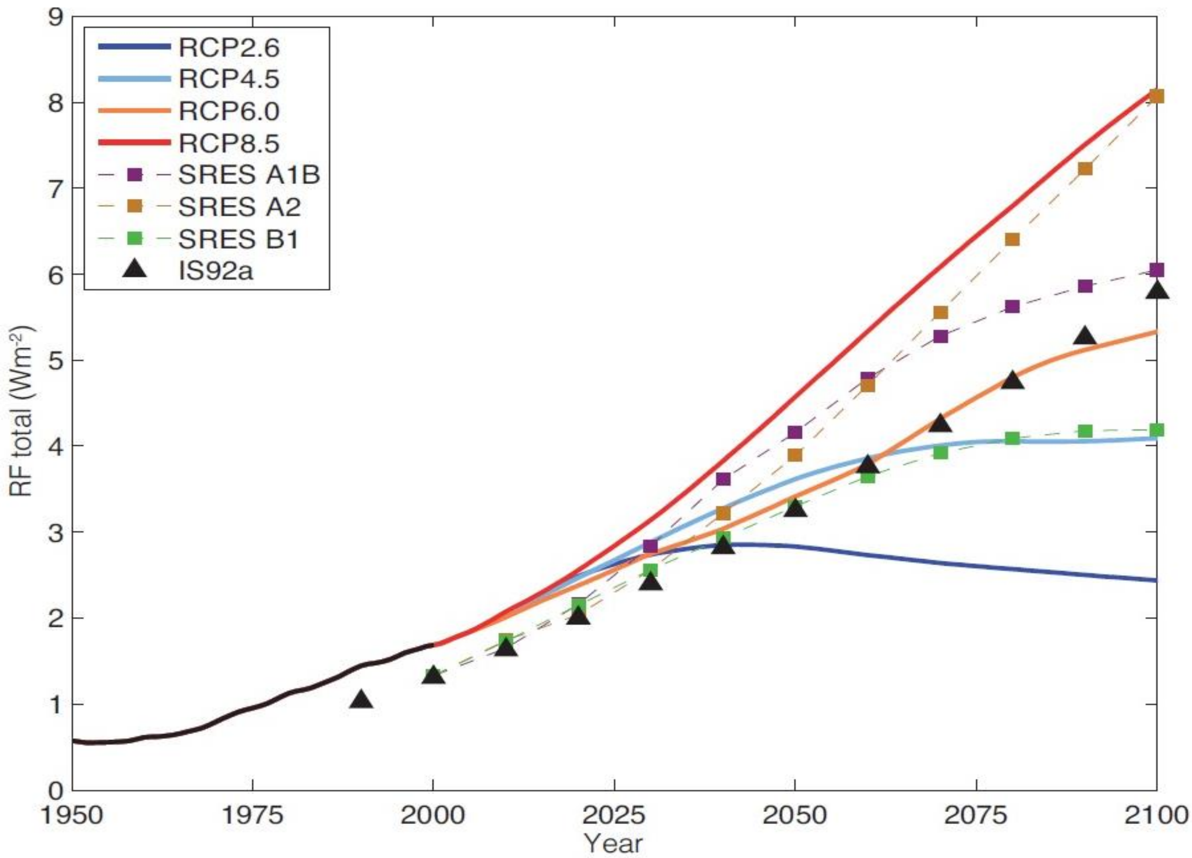

Figure 30: Historical and projected total anthropogenic radiative forcing (W/m^2) relative to preindustrial levels (about 1765) between 1950 and 2100 (Cubasch et al., 2013)**.**

A2 Global temperature change under RCP scenarios

Global warming during the 21st century is a consistent feature across the climate models for all RCP scenarios, see Figure 31 for the multi-model mean of global temperature change. The 20 years after 2005 show little variation in temperature change for all the RCP scenarios. At longer time scales the rate of global warming begins to depend more on the specified Green House Gases (GHG) concentration pathway. This increase is highest for the RCP 8.5 scenario with an increase of roughly 0.3°C per every ten years (Collins et al., 2013). The multi model mean for RCP 2.6 stays below 2°C above the 1850-1900 level for the entire 21st century. Between the period 1850-1900 and 1986-2005 a warming of 0.61°C has been observed. The stabilization of global warming under RCP 2.6 shows the potential of mitigation policies in stabilizing future global warming. RCP 4.5, RCP 6.0, and RCP 8.5 all exceed 2°C global warming during the 21st century with RCP 8.5 even exceeding 4°C by the year 2100 (Collins et al., 2013). Warming for the period 2046–2065 is slightly larger for the RCP4.5 scenario compared to the RCP6.0 scenario, this is consistent with its greater total anthropogenic forcing at that time (IPCC, 2013).

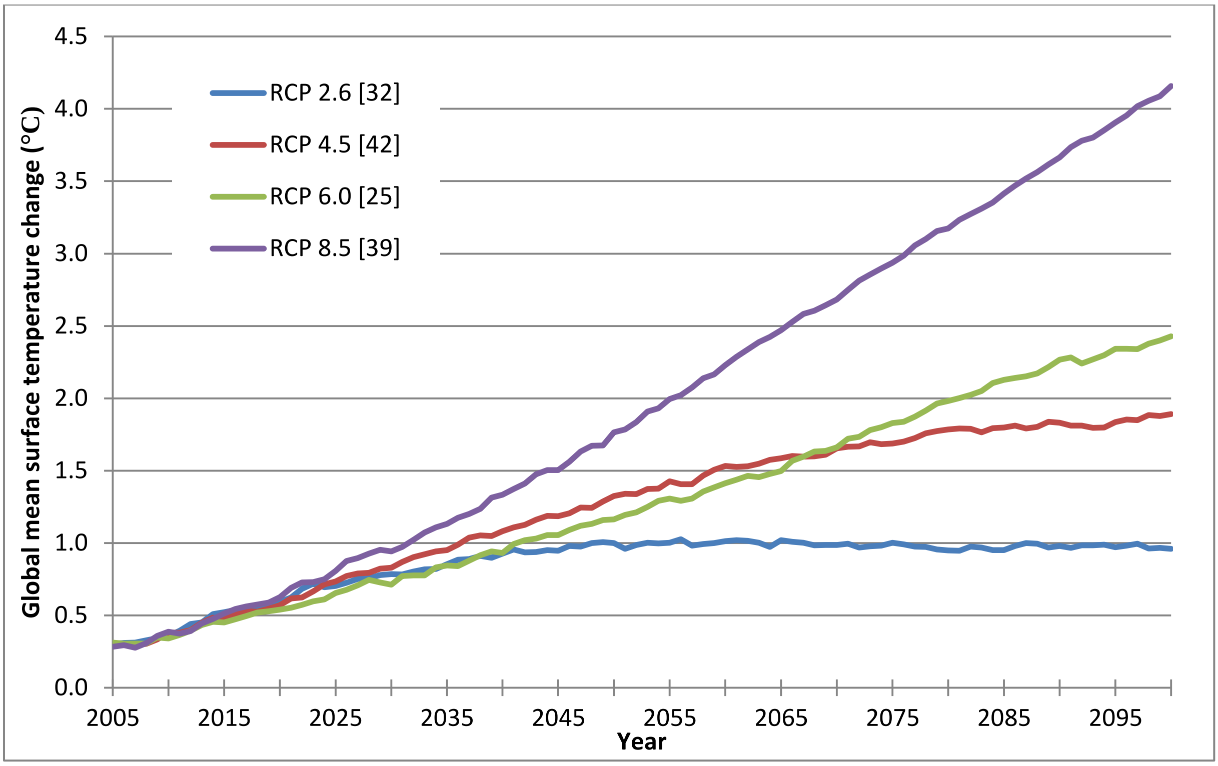

Figure 31: Multi model mean of global mean surface temperature change for the four RCP scenarios relative to 1986-2005. Number of models per scenario can be found in the brackets (data from van Oldenborgh et al., 2013)**.**

Appendix B Hurricane return period

Appendix B accompanies chapter 3.4 and presents the data used in the calculation of the hurricane return periods for North Carolina.

B1 Atlantic hurricane data

The Atlantic hurricane data is taken from the Atlantic Oceanographic & Meteorological Laboratory Hurricane Research Division. The chronological list of all hurricanes was last updated in February 2014 and includes all known hurricanes from the period 1851-2013. For this research hurricane data has been used starting in the year 1900. The reason for omitting the data from the 19th Century is because before 1900 towns and cities in some coastal states were sparse, hurricanes may have been underestimated in their intensity or missed completely for small-sized systems (Atlantic Oceanographic & Meteorological Laboratory: Hurricane Research Division, 2014)

Table 11: Chronological list of all hurricanes originating in the Atlantic Ocean and making landfall between the states of Texas and Maine for the period 1900-2013 divided by decade (Atlantic Oceanographic & Meteorological Laboratory: Hurricane Research Division, 2014)

Chronological List of All Hurricanes: 1900-2013					
Year	**Month**	**States Affected and Category by States**	**Highest cat.**	**Max Wind (kt)**	**Name**
1900s					
1900	Sep	TX, N4	4	120	"Galveston"
1901	Jul	NC, 1	1	70	-----
1901	Aug	LA, 1; MS, 1; AL, 1	1	75	-----
1903	Sep	FL, SE1, NW1	1	80	-----
1903	Sep	NJ, 1; DE, 1	1	70	-----
1904	Sep	SC, 1	1	70	-----
1904	Oct	FL, SE1	1	70	-----
1906	Jun	FL, SW1, SE1	1	75	-----
1906	Sep	SC, 1; NC, 1	1	80	-----
1906	Sep	MS, 2; AL, 2; FL, NW2; LA, 1	2	95	-----
1906	Oct	FL, SW3, SE3	3	105	-----
1908	Jul	NC, 1	1	70	-----
1909	Jun	TX, S2	2	85	-----
1909	Jul	TX, N3	3	100	"Velasco"
1909	Aug	# TX, S1	1	65	-----
1909	Sep	LA, 3; MS, 2	3	105	"Grand Isle"
1909	Oct	FL, SW3, SE3	3	100	-----
1910s					
1910	Sep	TX, S2	2	90	-----
1910	Oct	FL, SW2	2	95	-----
1911	Aug	FL, NW1; AL,1	1	70	-----
1911	Aug	SC, 2; GA, 1	2	85	-----
1912	Sep	AL, 1; FL, NW1	1	65	-----

1912	Oct	TX, S2	2	85	-----
1913	Jun	TX, S1	1	65	-----
1913	Sep	NC, 1	1	75	-----
1913	Oct	SC, 1	1	65	-----
1915	Aug	FL, NE1	1	65	-----
1915	Aug	TX, N4, C1; LA, 1	4	115	"Galveston"
1915	Sep	FL, NW1	1	80	-----
1915	Sep	LA, 3; MS, 2	3	110	"New Orleans"
1916	Jul	MS, 3; AL, 2; FL, NW2	3	105	-----
1916	Jul	SC, 2	2	95	-----
1916	Aug	TX, S4	4	115	-----
1916	Oct	AL, 2; FL, NW2	2	95	-----
1917	Sep	FL, NW3; LA, 2; AL, 1	3	100	-----
1918	Aug	LA, 3; TX, N1	3	105	-----
1918	Aug	NC, 1	1	65	-----
1919	Sep	FL, SW4, SE2; TX, S3, C3	4	130	-----
1920s					
1920	Sep	LA, 2	2	85	-----
1921	Jun	TX, C1, N1	1	80	-----
1921	Oct	FL, SW3, NW2, NE1	3	100	"Tampa Bay"
1923	Oct	LA, 1; MS, 1	1	70	-----
1924	Aug	* NC, 1; MA, 1	1	65	
1924	Sep	FL, NW1	1	75	-----
1924	Oct	FL, SW1, SE1	1	80	-----
1926	Jul	FL, NE2; SE1	2	90	-----
1926	Aug	LA, 3	3	100	-----
1926	Sep	FL, SE4, SW3, NW3; AL, 3; MS, 1	4	125	"Great Miami"
1926	Oct	* FL, SW1, SE1	1	75	-----
1928	Aug	FL, SE2	2	85	-----
1928	Sep	FL, SE4, SW3, NE1, NW1; GA, 1; SC, 1	4	125	"Lake Okeechobee
1929	Jun	TX, C1	1	80	-----
1929	Sp-Oc	FL, SE3, SW2, NW1	3	100	-----
1930s					
1932	Aug	TX, N4, C1	4	130	"Freeport"
1932	Sep	AL, 1; FL, NW1	1	75	-----
1933	Jl-Au	# TX, S1; FL, SE1	1	80	
1933	Aug	NC, 1; VA, 1; MD, 1	1	80	-----
1933	Sep	TX, S3	3	110	-----
1933	Sep	FL, SE3	3	110	-----
1933	Sep	* NC, 2; VA, 1	2	85	
1934	Jun	LA, 2	2	85	-----
1934	Jul	TX, S1	1	75	-----

1934	Sep	* NC, 1; NJ, 1; NY, 1	1	65	
1935	Sep	FL, SE5, SW5, NW2; I-GA, 1	5	160	"Labor Day"
1935	Nov	FL, SE2, NE1	2	85	-----
1936	Jun	TX, C1	1	70	-----
1936	Jul	FL; NW2; I-AL,1	2	90	-----
1936	Sep	NC, 1; VA, 1	1	75	-----
1938	Aug	LA, 1	1	65	-----
1938	Sep	NY, 3; CT, 3; RI, 3; MA, 2	3	105	"Great New England"
1939	Aug	FL, SE1, NW1	1	65	-----
1940s					
1940	Aug	TX, N2; LA, 2	2	85	-----
1940	Aug	SC, 2; GA, 1	2	85	-----
1941	Sep	TX, N3,C2	3	110	-----
1941	Oct	FL, SE2, SW1, NW1, IGA1	2	85	-----
1942	Aug	TX, N1	1	65	-----
1942	Aug	TX, C3, N2	3	100	-----
1943	Jul	TX, N2	2	90	-----
1944	Aug	NC, 1	1	70	-----
1944	Sep	NC, 2; VA, 2; NY, 2; CT, 1; RI, 2; MA, 1; NJ, 1	2	90	"Great Atlantic"
1944	Oct	FL, SW3, NE2, NW1	3	105	-----
1945	Jun	FL, NW1	1	70	-----
1945	Aug	TX, C2, S1, N1	3	100	-----
1945	Sep	FL, SE4, SW3, NE1	4	115	-----
1946	Oct	FL, SW2, NW1	1	75	-----
1947	Aug	TX, C1	1	70	-----
1947	Sep	FL, SE4, SW2, LA2, MS2	4	115	-----
1947	Oct	GA2, SC2, FL, SW1, SE1	2	90	-----
1948	Sep	LA1	1	70	-----
1948	Sep	FL, SW4, SE2	4	115	-----
1948	Oct	FL, SW2, SE2	2	90	-----
1949	Aug	*NC, 1	1	70	-----
1949	Aug	FL, SE4, SW1, NW1, NE1, GA1	4	115	-----
1949	Oct	TX, N2, C1	2	95	-----
1950s					
1950	Aug	AL1, FL, NW1	1	75	Baker
1950	Sep	FL, NW3, SW1	3	105	Easy
1950	Oct	FL, SE4, NE1	4	115	King
1952	Aug	SC, 1	1	78	Able
1953	Aug	NC, 1	1	78	Barbara
1953	Sep	ME, 1	1	65	Carol
1953	Sep	FL, NW1	1	70	Florence
1954	Aug	NY, 3; CT, 3; RI, 3; NC, 2	3	85	Carol

1954	Sep	MA, 3; ME, 1	3	90	Edna
1954	Oct	SC, 4; NC, 4; MD, 2	4	110	Hazel
1955	Aug	NC, 3; VA, 1	3	70	Connie
1955	Aug	NC, 1	1	75	Diane
1955	Sep	NC, 3	3	90	Ione
1956	Sep	LA, 2; FL, NW1	2	80	Flossy
1957	Jun	TX, N4; LA, 4	4	125	Audrey
1958	Sep	* NC, 3	3		Helene
1959	Jul	SC, 1	1	65	Cindy
1959	Jul	TX, N1	1	75	Debra
1959	Sep	SC, 3	3	120	Gracie
1960s					
1960	Sep	FL, SW4, NE2; NC, 3; NY, 3; CT, 2; RI, 2; MA, 1; NH, 1; ME, 1	4	115	Donna
1960	Sep	MS, 1	1	80	Ethel
1961	Sep	TX, C4	4	125	Carla
1963	Sep	TX, N1	1	70	Cindy
1964	Aug	FL, SE2	2	87	Cleo
1964	Sep	FL, NE2	2	108	Dora
1964	Oct	LA, 3	3	100	Hilda
1964	Oct	FL, SW2, SE2	2	95	Isbell
1965	Sep	FL, SE3; LA, 3	3	108	Betsy
1966	Jun	FL, NW2	2	78	Alma
1966	Oct	FL, SW1	1	80	Inez
1967	Sep	TX, S3	3		Beulah
1968	Oct	FL, NW2, NE1	2		Gladys
1969	Aug	LA, 5; MS, 5	5	140	Camille
1969	Sep	ME, 1	1		Gerda
1970s					
1970	Aug	TX, S3	3	108	Celia
1971	Sep	LA, 2	2	91	Edith
1971	Sep	TX, C1	1	75	Fern
1971	Sep	NC, 1	1	65	Ginger
1972	Jun	FL, NW1; NY, 1; CT, 1	1	75	Agnes
1974	Sep	LA, 3	3		Carmen
1975	Sep	FL, NW3; I-AL1	3	108	Eloise
1976	Aug	NY, 1	1	65	Belle
1977	Sep	LA, 1	1	65	Babe
1979	Jul	LA, 1	1	65	Bob
1979	Sep	FL, SE2, NE2; GA, 2; SC, 2	2	60	David
1979	Sep	AL, 3; MS, 3	3	108	Frederic
1980s					
1980	Aug	TX, S3	3	100	Allen

1983	Aug	TX, N3	3	100	Alicia
1984	Sep	* NC, 2	2	95	Diana
1985	Jul	SC, 1	1	65	Bob
1985	Aug	LA, 1	1	80	Danny
1985	Sep	AL, 3; MS, 3; FL, NW3	3	100	Elena
1985	Sep	NC, 3; NY, 3; CT, 2; NH,2; ME, 1	3	90	Gloria
1985	Oct	LA, 1	1	75	Juan
1985	Nov	FL, NW2; I-GA 1	2	85	Kate
1986	Jun	TX, N1	1	75	Bonnie
1986	Aug	NC, 1	1	65	Charley
1987	Oct	FL, SW1	1	65	Floyd
1988	Sep	LA, 1	1	70	Florence
1989	Aug	TX, N1	1	70	Chantal
1989	Sep	SC, 4; I-NC 1	4	120	Hugo
1989	Oct	TX, N1	1	75	Jerry
1990s					
1991	Aug	RI, 2; MA, 2; NY, 2; CT, 2	2	90	Bob
1992	Aug	FL, SE5, SW4; LA, 3	5	145	Andrew
1993	Aug	* NC, 3	3	100	Emily
1995	Aug	FL, NW2, SE1	2	85	Erin
1995	Oct	FL, NW3, I-AL 1	3	100	Opal
1996	Jul	NC, 2	2	90	Bertha
1996	Sep	NC, 3	3	100	Fran
1997	Jul	LA, 1; AL, 1	1	70	Danny
1998	Aug	NC, 2	2	95	Bonnie
1998	Sep	FL, NW1	1	70	Earl
1998	Sep	FL, SW2; MS, 2	2	90	Georges
1999	Aug	TX, S3	3	100	Bret
1999	Sep	NC, 2	2	90	Floyd
1999	Oct	* FL, SW1; NC, 2	2	95	Irene
2000s					
2002	Oct	LA, 1	1	80	Lili
2003	Jul	TX, C1	1	80	Claudette
2003	Sep	NC, 2; VA, 1	2	90	Isabel
2004	Aug	* NC, 1	1	70	Alex
2004	Aug	FL, SW4, SE1, NE1; SC, 1; NC, 1	4	130	Charley
2004	Aug	SC, 1	1	65	Gaston
2004	Sep	FL, SE2, SW1	2	90	Frances
2004	Sep	AL, 3; FL, NW3	3	105	Ivan
2004	Sep	FL, SE3, SW1, NW1	3	105	Jeanne
2005	Jul	LA, 1	1	65	Cindy
2005	Jul	FL, NW3; I-AL 1	3	105	Dennis
2005	Aug	FL, SE1, SW1; LA, 3; MS, 3; AL, 1	3	110	Katrina

2005	Sep	* NC, 1	1	65	Ophelia
2005	Sep	FL, SW1; LA, 3; TX, N2	3	100	Rita
2005	Oct	FL, SW3; FL, SE2	3	105	Wilma
2007	Sep	TX, N1; LA, 1	1	80	Humberto
2008	Jul	TX, S1	1	75	Dolly
2008	Sep	LA, 2	2	90	Gustav
2008	Sep	TX, N2; LA, 1	2	95	Ike
2010s					
2011	Aug	NC, 1	1	75	Irene
2012	Aug	LA, 1	1	70	Isaac
2012	Oct	* NY, 1	1	65	Sandy

Notes:

States Affected and Category by States Affected: *The impact of the hurricane on individual U.S. states based upon the Saffir-Simpson Hurricane Wind Scale (through the estimate of the maximum sustained [1-min] surface [10 m] winds at each state). TX S-South Texas, TX C-Central Texas, TX N-North Texas, LA-Louisiana, MS-Mississippi, AL-Alabama, FL NW-Northwest Florida, FL SW-Southwest Florida, FL SE-Southeast Florida, FL NE-Northeast Florida, GA-Georgia, SC-South Carolina, NC-North Carolina, VA-Virginia, MD-Maryland, DE-Delaware, NJ-New Jersey, NY-New York, PA-Pennsylvania, CT-Connecticut, RI-Rhode Island, MA-Massachusetts, NH-New Hampshire, ME-Maine. In Texas, south refers to the area from the Mexican border to Corpus Christi; central spans from north of Corpus Christi to Matagorda Bay and north refers to the region from north of Matagorda Bay to the Louisiana border. In Florida, the north-south dividing line is from Cape Canaveral [28.45N] to Tarpon Springs [28.17N]. The dividing line between west-east Florida goes from 82.69W at the north Florida border with Georgia, to Lake Okeechobee and due south along longitude 80.85W.) Occasionally, a hurricane will cause a hurricane impact (estimated maximum sustained surface winds) in an inland state. To differentiate these cases versus coastal hurricane impacts, these inland hurricane strikes are denoted with an "I" prefix before the state abbreviation. States that have been so impacted at least once during this time period include Alabama (IAL), Georgia (IGA), North Carolina (INC), Virginia (IVA), and Pennsylvania (IPA). The Florida peninsula, by the nature of its relatively landmass, is all considered as coastal in this database.*

Highest U.S. Saffir-Simpson Category: *The highest Saffir-Simpson Hurricane Wind Scale impact in the United States based upon estimated maximum sustained (1-min) surface (10 m) winds produced at the coast. ("TS" indicates that the system caused only tropical storm conditions in the United States, though it was a hurricane at landfall. See "&" below.)*

Maximum Winds: *Estimated maximum sustained (1-min) surface (10 m) winds to occur along the U. S. coast. Winds are estimated to the nearest 10 kt for the period of 1851 to 1885 and to the nearest 5 kt for the period of 1886 to date. (1 kt = 1.15 mph.)*

** - Indicates that the hurricane center did not make a U.S. landfall (or substantially weakened before making landfall), but did produce the indicated hurricane-force winds over land. In this case, central pressure is given for the time that the hurricane winds along the coast were the strongest.*

& - Indicates that the hurricane center did make a direct landfall, but that the strongest winds likely remained offshore. Thus the winds indicated here are lower than in HURDAT.

 # - Indicates that the hurricane made landfall over Mexico, but also caused sustained hurricane force surface winds in Texas. The strongest winds at landfall impacted Mexico, while the weaker maximum sustained winds indicated here were conditions estimated to occur in Texas.

Table 12: Number of hurricanes per Category and number of hurricanes to pass through North Carolina

Category	Total
Category 1 Hurricanes	81
Category 2 Hurricanes	44
Category 3 Hurricanes	46
Category 4 Hurricanes	18
Category 5 Hurricanes	3
All Hurricanes	192
Total Hurricanes to hit North Carolina	37

B2 Current and future hurricane return periods for North Carolina

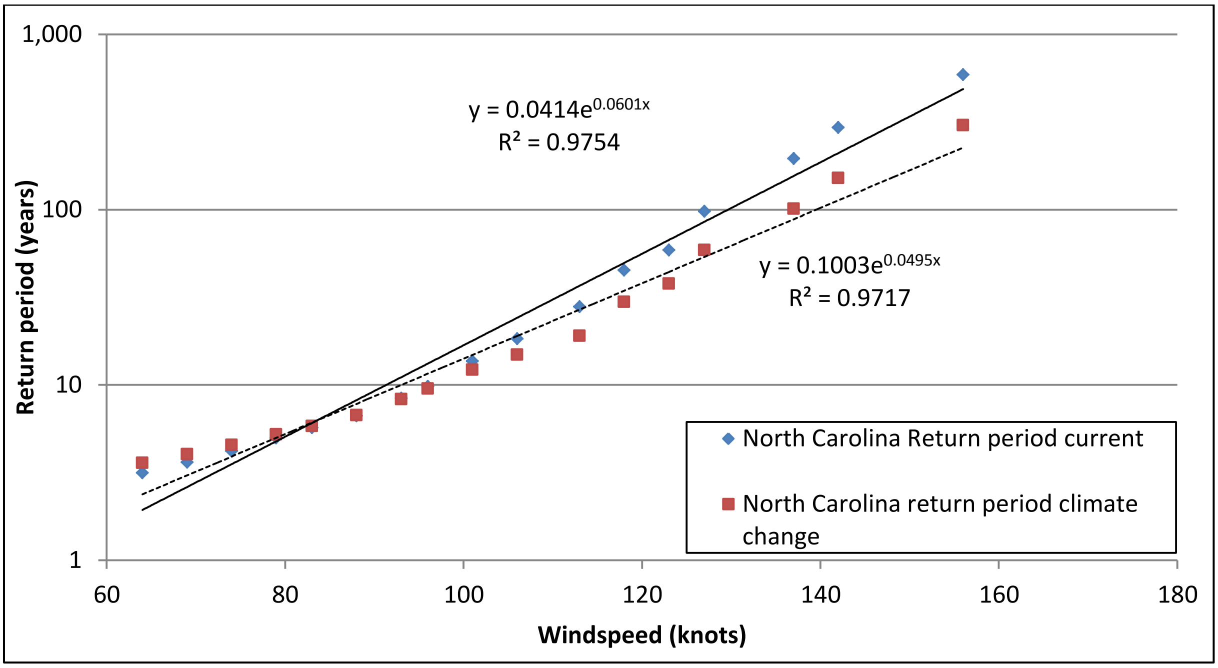

Figure 32: North Carolina hurricane return period. Wind speed plotted against the return period. The top formula accompanies the trend line for the current return period, the bottom formula accompanies the trend line for the future (2050) return period.

Appendix C RHEA model

C1 Visual representation of price negotiations in the RHEA model

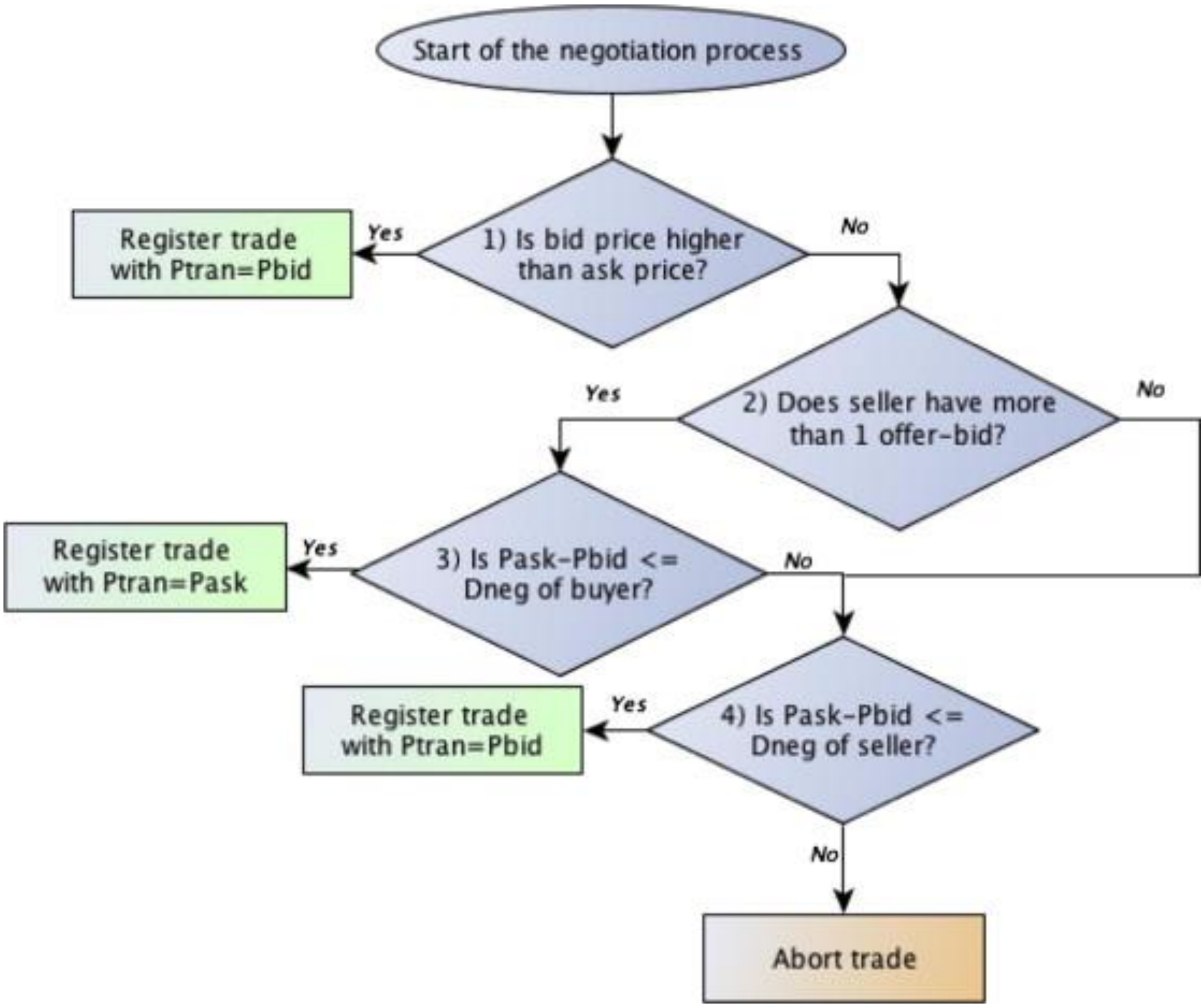

Figure 33: The simulation flow of the price negotiation process. (Filatova, 2014)

C2 Model input

Table 13: Input parameters and a description of these parameters. Settings for the input parameters used during the baseline simulation.

Input parameter	Parameter description	Parameter value
Landscape settings		
Case-study	Select a study area	USA-Beaufort
fraction_on_sale	Determine the share of owners who decide to become sellers, mean and standard deviation	0.14
sd_fraction_on_sale		0.01
NofBuyers	number of buyer agents at initialization	Equal to sellers
SellerChoice	Ask traders to become sellers based on a certain criteria	Random
newBuyerCoef	Determine how many of the newcomers to the area become buyers	0.7
Agents' settings		
Utility		Expected Utility
Budgets	Set households budgets according to a certain criteria	Empirical
fixedAlfa?	Determines whether agents have homogeneous or heterogeneous preferences for spatial goods or amenities	Normal distribution
fixedGamma?		Normal distribution
prefAlfa	Assign the preference for spatial goods over compositegoods	0.4
prefGamma	Assign the preference for environmental amenities	0.5
Gsd	Standard deviation t for prefGamma	0.05
Insurance	Is flood insurance taken into account	On
RealtorHedonics		Adaptive
Frequency	Set the time to pas per tick	Semi-annual
aDelta	Difference between bid and ask price, which buyer/seller is ready to accept in price negotiations	1
InputCurRS	Set the Random-seed	1108708898
Dynamic risk perception bias settings		
sameRPbias	Do all agents have the same risk perception bias?	Off
perception_change	Sets the risk perception bias	0.000
Sensitivity		
N of cells a buyer considers in her search		5
Years of mortgage		30
Travel costs per unit of distance multiplier		1

Appendix D RHEA code

In this chapter the changes made to the RHEA code can be found. New global variables as well as new pieces of code written for the model.

D1 Global variables

This section shows the new global variables that were introduced into the code, with a short description of their function.

Table 14: New variables added to the RHEA model

Variable	Function
tradeprice	Stores the value for which a property has been sold, for 1 tick
flooding100year	Allows to set the flooding probability for the current 100 year flood zone
flooding500year	Allows to set the flooding probability for the current 500 year flood zone
hurricane	Sets a random value to determine if a hurricane will occur in the current time step
counter	Counts the number of ticks that have passed since the last flood event, and is used to determine the discount coefficient
hurricane-counter	Counts the total number of hurricanes to occur in a single simulation
large-hurricane-counter	Counts the number of hurricanes large enough to flood the 500 year flood zone
perception_change	Allows to set the perception bias for the first time step following a hurricane
DC	The discount coefficient
ClimateChange	Allows to turn climate change on or off
avtradePriceFP0	Stores the average trade price in the FP0 zone for every time step
avtradePriceFP100	Stores the average trade price in the FP100 zone for every time step
avtradePriceFP100-CF	Stores the average trade price in the FP100-CF zone for every time step
avtradePriceFP500	Stores the average trade price in the FP500 zone for every time step
avtradePriceCoastFront	Stores the average trade price in the CoastFront zone for every time step
sumtradePriceFP0	Stores the total trade volume in the FP0 zone for every time step
sumtradePriceFP100	Stores the total trade volume in the FP100 zone for every time step
sumtradePriceFP100-CF	Stores the total trade volume in the FP100-CF zone for every time step
sumtradePriceFP500	Stores the total trade volume in the FP500 zone for every time step
sumtradePriceCoastFront	Stores the total trade volume in the CoastFront zone for every time step
NOfTradesFP0	Stores the number of trades in the FP0 zone for every time step
NOfTradesFP100	Stores the number of trades in the FP100 zone for every time step
NOfTradesFP100-CF	Stores number of trades in the FP100-CF zone for every time step
NOfTradesFP500	Stores the number of trades in the FP500 zone for every time step
NOfTradesCoastFront	Stores the number of trades in the CoastFront zone for every time step

D2 New code

This section shows the new pieces of code that were introduced into the RHEA model.

Storm procedure code

This procedure generates storms either random and in accordance with the return periods, or on set times. If a storm is generated the counter is set to 0 and if a storm is generated randomly the hurricane counters are updated in accordance with the size of the storm. A message is also displayed telling the user what kind of storm has been generated.

```
To storm
	ifelse Random-Storm = true
		[ifelse ClimateChange = true
			[set hurricane random-float 1]
			[set hurricane random-float -1]
			]
		[if (ticks = 10 or ticks = 60) [
			set counter 0]
		]

	if (hurricane <= 0.1164) and (hurricane >= 0.1)[
		set counter 0]
	if (hurricane >= -0.11) and (hurricane <= -0.1)[
		set counter 0]

	if ((hurricane <= 0.1164) and (hurricane >= 0.1)) or
	((hurricane >= -0.11) and (hurricane <= -0.1))[
		set hurricane-counter hurricane-counter + 1]
	if ((hurricane <= 0.1043) and (hurricane >= 0.1)) or
	((hurricane >= -0.102) and (hurricane <= -0.1))[
		set large-hurricane-counter large-hurricane-counter + 1]

	if (hurricane <= 0.1164) and (hurricane > 0.1113) [print "cat. 4 hurricane"]
	if (hurricane <= 0.1113) and (hurricane > 0.1043) [print "cat. 5 hurricane"]
	if (hurricane <= 0.1043) and (hurricane >= 0.1) [print "large cat. 5 hurricane"]

	if (hurricane >= -0.11) and (hurricane < -0.1064) [print "cat. 4 hurricane"]
	if (hurricane >= -0.1064) and (hurricane < -0.102) [print "cat. 5 hurricane"]
	if (hurricane >= -0.102) and (hurricane <= -0.1) [print "large cat. 5 hurricane"]
end
```

Count-up procedure code

This procedure updates the counter to accurately display the number of time steps that have passed since the last flood event. It also sets the discount factor (DC).

```
to count-up
	if counter <= 10[
		set counter counter + 1]
		set DC 1 - (0.4343 * ln counter - (6 * exp -13))
end
```

Risk perception bias code

This procedure determines the value of the risk perception assigned to the traders.

```
to perception-update
	ask traders[
	ifelse counter <= 10
		[ifelse sameRPbias = true
			[set A-RPbias (DC * perception_change)]
			[set A-RPbias random-normal (DC * perception_change) ((DC *
			perception_change) * (1 / 6))
				if A-RPbias < 0 [set A-RPbias 0]
				if A-RPbias > 1 [set A-RPbias 1]
			]
		]
		[set A-RPbias 0]
	]
end
```

Updating land traders procedure

In this procedure code has been added to track the simulation results.

The average trade price:

```
set avtradePriceFP0 (mean [tradeprice] of parcels with [(residential? = true) and
(probabilityOfFlood = 0) and (tradeprice > 0)])
set avtradePriceFP100 (mean [tradeprice] of parcels with [(residential? = true) and
(probabilityOfplooda = 1) and (tradeprice > 0)])
set avtradePriceFP100-CF (mean [tradeprice] of parcels with [(residential? = true) and
(probabilityOfFlooda = 1) and (coastalFront = 0) and (tradeprice > 0)])
set avtradePriceFP500 (mean [tradeprice] of parcels with [(residential? = true) and
(probabilityOfFloodx = 1) and (tradeprice > 0)])
set avtradePriceCoastFront (mean [tradeprice] of parcels with [(residential? = true) and
(coastalFront = 1) and (tradeprice > 0)])
```

The total trade volume:

```
set sumtradePriceFP0 (sum [tradeprice] of parcels with [(residential? = true) and
(probabilityOfFlood = 0) and (tradeprice > 0)])
set sumtradePriceFP100 (sum [tradeprice] of parcels with [(residential? = true) and
(probabilityOfFlooda = 1) and (tradeprice > 0)])
set sumtradePriceFP100-CF (sum [tradeprice] of parcels with [(residential? = true) and
(probabilityOfFlooda = 1) and (coastalFront = 0) and (tradeprice > 0)])
set sumtradePriceFP500 (sum [tradeprice] of parcels with [(residential? = true) and
(probabilityOfFloodx = 1) and (tradeprice > 0)])
set sumtradePriceCoastFront (sum [tradeprice] of parcels with [(residential? = true) and
(coastalFront = 1) and (tradeprice > 0)])
```

The number of trades:

```
set NOfTradesFP0 (count parcels with [(residential? = true) and (probabilityOfFlood = 0) and
(tradeprice > 0)])
set NOfTradesFP100 (count parcels with [(residential? = true) and (probabilityOfFlooda = 1)
and (tradeprice > 0)])
set NOfTradesFP100-CF (count parcels with [(residential? = true) and (probabilityOfFlooda = 1)
and (coastalFront = 0) and (tradeprice > 0)])
set NOfTradesFP500 (count parcels with [(residential? = true) and (probabilityOfFloodx = 1)
and (tradeprice > 0)])
set NOfTradesCoastFront (count parcels with [(residential? = true) and (coastalFront = 1) and
(tradeprice > 0)])
```