Master Thesis

submitted within the UNIGIS MSc programme
Interfaculty Department of Geoinformatics - Z_GIS
University of Salzburg

Coastal hazard – climate change-related implications from the combined parameters sea level rise, tides, and non-tidal residuals

An approach for assessing the total water levels at the coast of Houston (US) and Sydney (AUS)

by

Johannes Dietrich
106742

A thesis submitted in partial fulfillment of the requirements of the degree of
Master of Science – MSc

Advisor:

Dr. Christian Neuwirth

Munich, 01/13/2022

Acknowledgment

First of all, I want to express my extraordinary thanks to Dr. Christian Neuwirth, who agreed to support this very interdisciplinary master thesis project. You were very clear, supportive, and kind at all times and made this project realizable.

Dr. Jürgen Schimetschek led me through my entire one-and-a-half-year journey at Munich Re, first as Student Trainee and then also with my Master's Thesis Scholarship. Thank you for all the time and experience you shared with me, I am very grateful, that I had such an experienced mentor, who kept an eye on me and supported me every time I needed it.

Technical support and invaluable GIS advice came from Stefan Wiesmeier, who also helped to provide the right technical infrastructure for my data, without the project could not have been finished at this time!

I want to thank also Ernst Rauch, Chief Climate Officer and Head of Climate Change Solutions Development at Munich Re for supporting my thesis project by funding the Scholarship and Dr. Christof Reinert, head of Risk Management Partners at Munich Re for the trust in my work and the belief in a valuable outcome of my thesis for the department.

Thanks even to all other colleagues from Munich Re for the continuous support and inspiration, it was a very instructive and inspiring time.

Johannes Dietrich

Munich 01/13/2022

Science Pledge

I hereby declare that the thesis is entirely the result of my work. I have cited all sources I have used in my thesis, I have always indicated their origin. This thesis was not previously presented to another examination board and has not been published.

Johannes Dietrich
Munich 01/13/2021

Content

FIGURES

Tables

Abbreviations

AR – Assessment Report

CMIP – Coupled Model Intercomparison Project

ECS – Equilibrium Climate Sensitivity

ESL – Extreme Sea Level

GHG – Greenhouse Gas

GIA – Glacial Isostatic Adjustment

GMSL – Global Mean Sea Level

GTSR – Global Tide and Storm Reanalysis

HAT – Highest Astronomical Tide

IPCC – International Intergovernmental Panel on Climate Change

MSL – Mean Sea Level

MHHW – Mean Higher High Water

NOAA - National Oceanic and Atmospheric Administration

NTDE – National Tidal Datum Epoch

PDE – Partial Differential Equation

RCP – Representative Concentration Pathway

RSL – Relative Sea Level

SD – System Dynamic

SLR – Sea Level Rise

SROCC – Special Report on the Ocean and Cryosphere in a Changing Climate

SSD - Spatial System Dynamic

VML – Visual Modelling Language

Abstract

This study investigated possible total water levels (TWL) over Mean Sea Level (MSL) under sea-level rise (SRL) in the years 2050 and 2100 in different emission scenarios from IPCC at the coasts near Houston (US) and Sydney (AUS). For the calculation of the TWL spatially relative sea-level rise data from the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), non-tidal residuals and the highest astronomical tide data were used. Non-tidal residuals were assigned to a 90.5 year return period with the Weibull distribution from a 180 years time series. In addition to a simple additive model (AM), different ways for the consideration of possible non-linear changes induced by SLR were investigated and calculated at both sites. Non-linear relations were derived from empirical studies assuming that SLR increases tidal amplification more than the additional SLR in the future and the increased tidal amplification could lead to lower meteorologically forced residuals. The results show slight changes in occurring water heights under the additive and non-linear model results, especially as a spatial disparity. But there is only medium confidence about the generalizable of these non-linear effects and how high the empirical evidence is there. Quantification of the strength of the influence of SLR on those parameters is not possible as there is only low confidence about the exact character. Additionally, the effects might be not uniform and there are already exceptions documented. Nevertheless, the study can show the importance of the consideration of non-linear effects and lies a foundation for a parametric model for coastal hazard assessment in times of SLR.

1. Introduction

The term “Coastal Hazards” combines several perils related to active hydrological threats for example as tidal variability, storm surges, climate-driven sea-level rise change, or tsunami. The research field of coastal hazards even considers the consequences of these hydrological parameters and their impact on coastal regions such as coastal erosion, shoreline changes, rising groundwater levels, and inundation. (Stephens et al., 2017)

It must be stated, that in this thesis coastal hazards, in a narrow sense, are understood as phenomena, which occur from meteorological and climate-driven threats, where seismic-induced events as tsunamis are not considered. This differentiation is important as the selection of observed parameters and methodologies is affected by this definition.

Not only acute events as severe inundation caused by non-tidal residuals in sea level as storm surges but also long-term effects as erosion show the need for investigating and understanding the dynamic of coastal changes and the change of their causing parameters. (Toimil et al., 2017)

The most important chronic parameter driving coastal hazards in the future is the rising sea level and the possible effect on other hydrological parameters as tides and storm surges. (Benveniste et al., 2019)

Recent publications of the Intergovernmental Panel on Climate Change (IPCC) under the contribution of several international working groups increased evidence about discussed scenarios of rising sea levels. The trend of rising global mean sea level (GMSL) between 1901 and 2018 of increased 15-25cm is expected to be extended in the future as shown in the Sixth Assessment Report (AR6) of IPCC. Low carbon emission scenarios expect an increase up to 55cm and high carbon emission scenarios changes of GMSL level up to 1.02m in 2100 relative to 1995-2014 reference period. Within high emission scenarios, there is high uncertainty about possible dynamics, which could rise the change in global mean sea level up to 5m until 2150 with low confidence. (Arias et al., 2021)

In contrast to this sea level remained relatively stable in the last 2000-3000 years, which encouraged settlements and economic activity near the coast and leads to higher exposures under the new premise of rising sea level now. (Stephens et al., 2017)

Scyphers et al. (2019) show that only in the United States of America 1.3 Million people are identified in the highest quartile of exposure towards hydrological perils near the coast and Hinkel et al. (2014) calculate 0.3-9.3% of the global gross domestic product (GDP) can be affected by coastal floods in 2100 based on Coupled Model Intercomparison Project 5 (CMIP5) data.

In particular, New York City as a global metropolitan area is facing increasing future inundations through sea-level rise even when occurring cyclones are expected to move offshore more likely within the next centuries. Especially the likelihood of quite strengthened storms, if they do a landfall, will raise sea levels significantly compared to preindustrial levels. (Garner et al., 2017)

Kerle & Müller (2013) additionally show that the trend of metropolitan agglomeration will extent the risk of severe impacts in global megacities. Global urbanization trends even rise complexity for identifying exposure, vulnerability, and suitable actions for building up more resilience.

Complexity and lack of suitable data cause a gap in the monitoring of coastal hazards on a global scale (Benveniste et al., 2019). It is necessary to understand coastal systems on bigger scales better than before to find ways for adaption to prevent severe damage for humans, the environment, and the economy.

This thesis addresses the gap of regional studies with partly hydrodynamic components and potentially scalable methodology researching potential hazards for coastal regions under changing characteristics of the hydrological main parameters due to climate change.

Often hydrodynamic models are assumed as time inefficient for modeling data on a global scale, because of the effort of performing simulations for large amounts of data. (Chen et al., 2021)

Some publications assume an additive relationship between the main hydrological parameters as Garner et al. (2017). For considering possible non-additive and counter-intuitive developments of the relation of investigated parameters the methodology of System Dynamics is used to derive possible characteristics of the coastal hazards and develop a System Dynamic model to approach more likely occurring water heights in the future.

First, this thesis addresses the question of nonlinearity of coastal hydrological hazards considering tides, sea-level rise, and non-tidal residuals and if they can be modeled in the two investigation sites Houston (USA, Texas) and Sydney (AUS, New South Wales), assuming mostly divergent characteristics of both sites regarding physical appearance and behavior of investigated variables. For this analysis, the complex system is divided into variables and the relation is primarily investigated as a non-spatial process.

Both investigation sites are chosen because they are well-investigated and hit by storm events regularly. Also, good reference data and information about the hydrological characteristics as tides and the bathymetry can be provided for both sites. Mostly important for choosing the sites was the fact, that Sydney is more exposed to extratropical storms and Houston is a classic example for being heavily threatened by tropical storms regularly. Additionally, the tidal pattern and the bathymetry with its coastal shelf structure and shallow water processes are very different at both sites, which could serve as a good example for regional differences.

Mainly, it will be questioned, how the relationship of the hydrological main parameters could be characterized mathematical, what does this imply for changing conditions in the future, and how it can be compared to other studies. It is assumed, that changes in sea level will affect the occurring wave heights of storm surges and the tidal variability. Further, it is assumed, that not only positive feedback loops are increasing the water heights, but also rising water depth is affecting the height by contributing with negative feedback loops and mitigating possible increases of the water height. This possible nonlinearity of the system could lead to not expected and counter-intuitive behavior in future coincident storm, tidal and sea-level rise situations, which have to be understood to provide the needed information for disaster prevention and long-term planning.

Additionally, the character of the nonlinearity possibly differs on a local or regional level in respect of the site. A very important part there is the different severity of the impacts on total water levels regionally, which could be the result of different macro-hydrological patterns as tides and regularly occurring storms.

For investigating this complex question, an approach is chosen for reducing system complexity. The biggest challenge is the exploration of suitable data, with global coverage and temporal resolution for deriving suitable statistical metrics which represent the range of probability and severity of the parameter in a scientifically acceptable manner. Global coverage of the data is intended to prepare a global data product for the assessment of changing total water heights due to rising sea levels.

For deriving parametric relations, international studies are used from different regions. Following that, the question of generalization and scalability of the approach for global usage is followed and if general parametrical models on a regional scale are applicable for hazard modeling will be also considered.

After the extraction of the possible spatial non-uniformity and non-additivity of the driving parameters sea level rise, non-tidal residuals, and tidal characteristics, the question for a spatial integration of the mathematical relation will be investigated using data for each of the variables.

For this, the equation will be used finally to discretize the coastal hazard in an offshore total water level (TWL) over mean sea level (MSL) raster for the study areas using input datasets for the regions, but which have also global coverage. Within this step, the subsidiary question of connected problems of spatially discretizing hydrological phenomena is included and if this approach leads to reliable and comparable results.

2. Coastal hazard

2.1. Model landscape

There are many models, terminologies, and frameworks about hydrological modeling and approximation of hydrological real-world conditions in complex models. Models and approaches are differentiable in their purpose and their overall approach for the abstraction of a real-world phenomenon. In this case, this means mainly the concepts and the differentiation between “Eulerian” and “Langrangian” models. Following that, a model overview is provided by differentiating the set of used variables, differentiating between eulerian or lagrangian modeling in the spatial perspective, and the overall kind of the quantitative approach (e.g., stochastic, deterministic). In order of the geospatial focus of the thesis, purely physical and simulational driven models will be neglected in comparison to so-called parametrical or more deterministic models.

Nevertheless, it is clear, that the model is limited to the underlying physical assumptions and reductions made for creating the modeling approach.
Røed (2019) shows the basic assumptions for the computational modeling of hydrological processes. At this point, it is stated that most of the used models do not necessarily implement their method into a terminological framework as Røed (2019) but it is necessary to use a basic terminological framework to define the technical and scientific surroundings and limitations of each model category or type. The governing assumptions should be mentioned but not discussed at this point as they define main variables and their characters in a physical way. (Røed, 2019)
Certainly, the point of view on the investigated system is not less important than the physical governing and definition of observed systems. Røed (2019) also shows the prerequisite of boundary conditions of spatial areas because especially hydrological phenomena are settled into a spatial relation.
From the spatial point of view, two types of perspectives can be derived: particles are moving in space and time and follow certain relations to each other while their behavior is mainly dependent on their movement (lagrangian). The other perspective tries to discretize the phenomenon into spatial entities and approximates the behavior in these spatial entities (eulerian).
It depends on the modeling approach and how the model is tried to be set up mathematically and computationally. Bontempi & Faravelli (1998) use the terminology Lagrangian and Eulerian for these two different perspectives on the observed systems. Langrangian describes the motion of a fluid particle in space and Eulerian particles in a fixed and finite spatial entity. Both perspectives established different possibilities of numerical operations and also showed their limitations and challenges. The Eulerian perspective limits the spatial dynamics of a system into the fixed spatial entity, which leads to the problem of approximative solutions at the borders, which (Røed, 2019) calls “boundary conditions” (Røed, 2019). This problem of spatial discretization of the overall system dynamic is usually tried to be solved by partial differential equations (PDE), which function as approximative bridgings between the spatial finite entities and lead to a more or less approximative overall description of the dynamic of the system. (Bontempi & Faravelli, 1998)

Breaking it down to an individual formulation, usage of PDE is like an interpolation because it approximately tries to connect the mechanisms of fixed and finite spatial entities for approaching the continuous real-world phenomena.

Neuwirth et al. (2015) connect this modeling of spatial phenomena with the terminology of Spatial System Dynamics (SSD). SSD is a deterministic approach connecting Visual Modelling Language (VML) and deterministic system views in a spatial environment enabling the user to gain an in-depth understanding of mathematical abstraction of the system's behavior. (Neuwirth et al., 2015)

Neuwirth et al. (2015) derived three different domains where SSD models are mostly used: local processes, diffusion processes, and processes that change the underlying structure itself.

A general model overview with a suggested typology is given in the following section to describe different widely used model approaches in the specific field of coastal hazards. The typology is focused on the overall domain of coastal hazard models and related geospatial modeling.

The first parameter of the typology is, how the model defines the composition of coastal hazard by a selection of considered parameters and factors. The next questions are, on which scale the model investigates the hydrological hazard and if it is a deterministic or more stochastic approach or a mixture of both. Finally, it is tried to differentiate between the target variables of the modeling (inundation areas onshore, total water heights offshore, wave height at the coastline from runup behavior, etc.).

A differentiation between Lagrangian and Eulerian processes in this setting is even more challenging and can be made only on an individual basis because of the widely spread usage of models in between this terminology. Because of this, no direct categorization in this field will be made avoiding terminological confusion.

Table 1 shows a suggested typology of models by scale.

Table 1: Basic hydrological coastal hazard models on different scales

Scale	Description	
Local	A deterministic model for offshore total water height calculation with tides, surges, and sea-level rise (Example: (Hakkou et al., 2019)	Hydrodynamic (simulative, probabilistic) model for inundation calculation onshore using tides, surges, sea-level rise, and run up behavior parameters (Example: (Lyddon et al., 2019)
Regional	No direct approaches because it is the border between extensive hydrological (physical) modeling and climate circulation models	
Global	Reanalysis (probabilistic) model for global offshore extreme water heights using global tide and surge model data with climate models (e.g., atmospheric pressure, wind speed) (Example: (Muis et al., 2016)	
Multi	Chain of models with different scales combining deterministic and probabilistic approaches (Example: (Torresan et al., 2019)	

The suggested typology orders the models oriented on their scale, as it is assumed, that the scale is the most important parameter for the choice of the modeling approach. In the given cases, it can be derived, that mainly physical simulation approaches, which consider hydrodynamic details, are only possible on local levels due to often remaining computational efforts. Lyddon et al. (2019) show an example for a model from the local category with physical and simulative components. By considering the run-up behavior the model gets more complex and enables the more detailed calculation of onshore inundation. Lyddon et al. (2019) choose a further target variable on a local scale by calculating the inundation onshore. Because of this target variable, the model also considers the run-up behavior next to tides and storm surges. It can be stated, that they calculate one more step in comparison to Hakkou et al. (2019), who aims the calculation of the total water height offshore near the coast. In this case, also tides and storm surges are considered variables, but also sea level rise as an additional variable. Hakkou et al. (2019) also, use a less complex approach and no hydrodynamic calculation. This means especially the assumption of just additive relation between the investigated variables.

Regional models are a special case, as they have no real application field and are between the overall climate circulation models and the complex hydrodynamic local models. Some models use a mixture of models from different scales even without regional downscaling. For example, Garner et al. (2017) combined data of global climate models (CMIP5) in a regional use case in New York City for assessing the flood hazard through sea-level rise and climate-driven changes of storm surges.
Global models combine several datasets and merge them with interpolation techniques, which leads to reanalysis datasets on a global scale. Muis et al. (2016) for example, use global tide data together with atmospheric reanalysis data to calculate a global tide and surge reanalysis (GTSR) dataset.
Another possibility, which is similar to the approach of Garner et al. (2017), is to use model chains ordered after scale. Torresan et al. (2019) use this approach for something as a model cascade beginning at global climate models, regional circulations, and further down to local hydrodynamic models.
There are multiple challenges for direct hazard assessment on a sub-regional scale. While climate change-associated developments of main driving parameters are only assessable on a supra-regional or global scale, a usable hazard estimation is needed and calculable under consideration of local and sub-regional processes and characteristics. This chain of assumptions connecting these different scales and model types has to be considered according to model immanent uncertainties. Even if there is no model chain implied directly, several assumptions are made by normally referring to global climate models. (Torresan et al., 2019)
In the suggested model typology only models with more active hydrological variables were considered, because the focus of this work is set on the hydrological hazard and on the risk or vulnerability which would also encompass passive parameters for example shoreline type, subsidence, population density, and economic activity in the area.
Benveniste et al. (2019) show more examples of parameters are involved in the complex dynamical systems of coasts. These so-called forcing factors are divided into anthropogenic and natural ones. In the field of natural factors, the interaction of oceanic and inland water plays an important role in sediment transport and

expected onshore inundations. On the other hand, there are several anthropogenic factors as land use associated soil sealing or building density. (Benveniste et al., 2019)

Under consideration of these multiple factors, the given typology is of course a reduction of the physical and multifactor complexity of the coastal hazard system. It is the question of the target variable, model extent, and complexity, which variables are considered, and how it is intended to model them.

Another perspective for a better understanding of the dimensions of modeling extreme sea levels for further modeling of onshore risks is given by McInnes et al. (2016).

Figure 1 below shows the differentiation between spatial and temporal scales and the causes for the emergence of extreme sea levels.

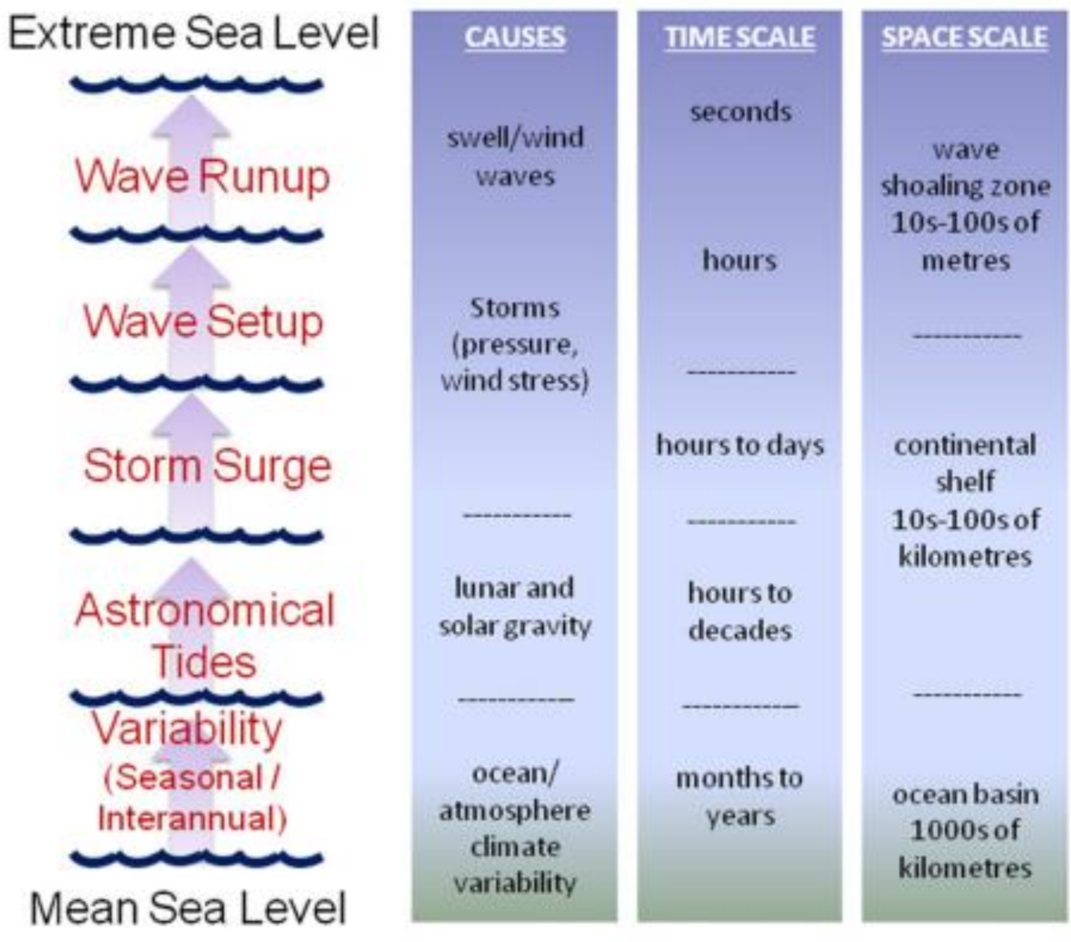


Figure 1: "Oceanic phenomena that contribute to the total water levels at the coast during an extreme sea-level event, their causes and the time and space scales over which they operate" (McInnes et al., 2016)

McInnes et al. (2016) also point to another dimension, which decreases the possibility to get a suitable overview of the model landscape. In Figure 1 mean sea level (MSL) is used as the baseline for modeling further steps approaching the extreme sea level. The hydrological parameters are highly variable and extremely relative depending on the perspective and the data, depending on the circumstance of measurements and applied inter- or extrapolations. There are several defined compositions of typically used parameters like MSL, but they can vary because of the underlying data. It is questionable if these parameters are differentiable so sharply as shown in Figure 1. Parameters as astronomical tides are idealized extreme values with high spatial relativity and are not sharply differentiable from meteorological forcing for example. This problem of differentiating certain parameters from each other which might also correlate to each other has to be kept in mind when it comes to setting up any kind of model for hydrological purposes.

With this background, it is decided to choose the active parameters tides and sea-level rise, the acute occurring variable of non-tidal residuals, and the regional characteristic of the bathymetry as forcing factors in the model, which is outlined in 3.2 and discussed under point 5. It can be anticipated at this point, that the model of this work is more aimed at the center of the scales and causes of Figure 1 and will not consider any run-up dynamics or onshore inundation modeling.

Detailed information about the parameters and the properties of the chosen datasets for further calculations is described under 3.1. Overall climate change-related developments of the variables and the dependency on the ongoing climate change science and recent publications will be described in the following chapter 2.2.

2.2. Coastal variables and climate change

To understand the key point of the investigation it is indispensable to set the chosen active factors of the coastal hazard system in a bigger picture of climate change to understand the main assumptions, which mechanisms are engaged and assumed to be underlying, and how they might be characterized.

In anticipation of the choice of the parameters tide, sea-level rise, and storm surges, the chapter will only describe the climate change relations and expected behavior of these factors.

As climate science is quite a science of approximation using methods from various fields of science, the expected variables and their behavior will be described under consideration of certain scenarios defining the probability of the behavior under the assumed change of global climate parameters. Indeed it is clear, that this has to be reduced to the necessary information needed to understand the overall framework of deriving the variables' expected behavior.

The main source of macroclimate change prediction will be from the International Intergovernmental Panel on Climate Change (IPCC) or oriented closely on its publications.

The latest publication (est 09/20/2021) is the Technical Summary of the Sixth Assessment Report (AR6) of the IPCC (Arias et al. 2021). Due to ongoing discussions in the scientific community about the new model generation and assumptions for example about the Equilibrium Climate Sensitivity (ECS) of the integrated Coupled Model Intercomparison 6 (CMIP6) and the recent publication of the first version, it is decided to orient more on the predictions of Fifth Assessment Report (AR5) (Pachauri and Meyer, 2014). Schlund et al. (2020) give an example for the ECS discussion and possible alternatives. ECS is the assumed temperature change in case of a doubling of the CO_2 concentration in the atmosphere at a certain point.

In some cases, models of CMIP6 are more climate-sensitive than observed in CMIP5 leading to a higher temperature range and higher upper limit. (Arias et al. 2021)

Nevertheless, the AR5 can be seen as a more scientific committed, and well-discussed basis for climate science without significant and undiscussed statistical outliers as the sixth generation.

IPCC divides the possible climate change into different scenarios connected to the emitted greenhouse gases (GHG). Within AR5 there are four main scenarios. Two mid-scenarios in the field of moderate to high (4.5 and 6.0) emission, one low emission scenario (2.6), and one worst-case scenario (8.5). Scenarios are also called Representative Concentration Pathway (RCP) standing for the concentration of carbon dioxide in the atmosphere and the related changes of main climate parameters based on the ECS. From this scenario-based concentration and the implications made from the ECS, parameters at different time points can be modeled or even changes to reference periods or points in time. (Pachauri and Meyer, 2014)

Based on IPCC´s AR5, the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) is a scientifically well-committed base for sea-level rise and overall oceanic changes within the models of CMIP5 (IPCC, 2019).

For the sea level, the question of relativity and definition is an important factor. Farrell & Clark (1976) have shown the divergent development and creation of non-consistent sea level rise change patterns on a global scale. This points out, that there is no uniform or consistent change of sea level on a global scale even under the assumption of non-rotational earth models.

The regional difference can be up to 30% in GMSL and those side effects have to be mentioned as factors of uncertainties which can lead to further distortion calculating the sea level and its exact change in different scenarios. (IPCC, 2019).

In the last years also effects on global mean sea level (GMSL) calculations, as an important benchmark variable for publicly discussed climate change development, also incorporate the significant effect of ocean eddies on it according to van Westen & Dijkstra (2021).

These factors are considered by SORCC and derived data based on the scientific approximation of the phenomenon of sea-level rise. Recent satellite altimetry investigations by Dettmering et al. (2021) in the north sea also confirmed the approximation of sea level using glacial isostatic adjustment (GIA) assumptions as also IPCC does (IPCC, 2019). The finally derived variable of sea-level rise considering the previous factors is defined as Relative Sea Level Rise (RSLR) and commonly used for hydrological hazard estimation. In contrast, GMSL is mostly given for assessing the global change but is not suitable as a parameter for a regional or local impact investigation for SLR.

According to the SORCC, GMSL accelerates rising driven by collapsing ice shields in Greenland and Antarctic in the last decades. This can be identified as the main forcing factor for sea-level rise before the thermal expansion of the oceans. (IPCC, 2019)

Predictions of IPCC AR6 assuming a range of increasing sea levels in the models between 0.55-1.02 meters in 2100 relative to the 1996-2014 reference period. This prediction and most of the underlying models are mostly consistent with the predictions made in SROCC. (Arias et al. 2021)

There is medium confidence by SORCC about the direct influence of sea-level rise to extreme wave heights in the period 1985-2018, but high confidence about increasing probability of high water levels associated with severe storm events. (IPCC, 2019)

So, measures in the global tide gauge network identify the regional sea-level rise as the most likely responsible forcing factor for extreme sea levels in the 20th century. (Arias et al. 2021).

Regional studies increased evidence about the possible contribution of sea-level rise to extreme water height associated with storm events. Important in the occurrence of extreme sea levels is the regionality of the forcing factors like storms and consequently with RSLR a variable in use, incorporating this spatial disparity of the phenomenon.

The contribution of storm events to extreme sea levels is a complex question, which is divided into two figures here. The first is the question of possibly increasing storm risk on a regional scale at all. The second is the contribution to extreme water heights near the coast of the possibly more likely occurring storms. This differentiation of the storm variable is made to distinguish between the question of macro-scale climate system change and the more hydrodynamic and regionally driven question of the impact on other forcing factors of the complex coastal system. For avoiding any redundancy, hydrodynamic questions around the contribution of storms on extreme water height will be investigated mainly in the model methodology part (3.2).

Assumed trends of a general increasing probability of storm occurrence due to climate change on a global scale, are not proven with high confidence at all. Pertinent literature shows, depending on the region, a more varying picture of the situation than commonly expected. For a suitable assessment, which contribution storms could have on water levels, the probability of their occurrence and additionally the probability of their landfall must be considered.

In a case study about hurricane Rita in the northern Gulf of Mexico, it was proven, that there is an influence on the water levels from the circumstance of the landfall of the storm. (Rego & Li, 2010)

Garner et al. (2017) incorporated the increased probability of storms moving offshore at the latitude of New York following implications of CMIP5 data.

More generally Wang et al. (2017) showed possibly climate-related changes in baroclinity, which will lead to a poleward shift of storm tracks in the northern Pacific and Atlantic. It is a widely common observation, that there could be a poleward shift of storm events. This poleward shift can come with a deceleration of the storm's movement, which would consequently lead to higher damages in populated areas because they could be hit by the storm activities over a longer time in the occurring storm event. This assumption is connected to several uncertainties coming up with various interdependencies of large circulations and parameters in the climate system related to climate change. But it shows also possibly occurring additional effects, strengthening the future impact of storms. (Zhang et al., 2020)

The poleward shift is also backed by Lee et al. (2020) for the typhoon regions in the western North Pacific.

The frequency of storms and the storm tracks are also only well interpretable in connection to changes in the distribution of the storm severity to the overall storm occurrence in certain regions.

Ongoing investigations and discussions about the frequency of the storms and the contribution of severe storms on the overall number and climate-related changes can be observed with higher confidence according to several studies. Analysis of satellite-based storm intensity data since the 1980s has shown an intensification of storms globally. (Vecchi et al., 2021)

Vecchi et al. (2021) also discover possibly distorting century-wide amplifications of storm frequency and intensity in connection to the north-Atlantic basin. This masking effect additionally impeds a risk assessment with higher confidence.
Overall, basins and their key position in calculating changes in storm occurrence probability underline the regionality of the ongoing development.
The regional individual characteristic of tides and geometry of the coastline are factors for the influence of the storms on the water levels. It is shown, that the construction of tidal variability is also connected to the probability of coinciding with an occurring storm event near or at the coast, which further mainly influences the total water heights. (Rego & Li, 2010)
To sum up the current situation in the area of risk assessment of storms, there are identifiable trends, varying in their significance and strongly dependent on their regional system. Additionally, high multidecadal variability of trends as shown for example by Vecchi et al. (2021) for the North Atlantic basin, rises complexity and lowers the level of confidence about the direct contribution of anthropogenic forcing on storm activity. Following that realization, it is very important to focus also on the methodology for understanding the relation of other parameters with storms to adapt future investigation results and storm trend identification with increasing confidence fastly.
Related to these uncertainties, the usage of certain storm trend data for future climate projections considering different scenarios of anthropogenic contribution has to be indicated while used with other data in multi-parametrical models.
Due to the immanent uncertainties coming with storm surge prediction, it is decided to focus more on the meteorological forced baseline with the parameter of non-tidal residuals.
For preventing confusion, it is remarked, that non-tidal residuals are not the same as storm surges, as non-tidal residuals are more an average meteorological contribution to the sea level with continuous occurrence. In contrast to this parameter, storm surges can be defined as extraordinary outrages of the sea level forced by very low atmospheric pressure and high wind speeds with specific directions. Non-tidal residuals are therefore more the baseline of the extreme water level hazards and can be seen as a precondition for estimating storm surge heights in relation. (Haigh, 2017)

As tides affecting also the occurrence of extreme water levels near the coast, possible changes in tidal variability and range which are possibly connected to climate change, have to be understood.
From tides, there can also occur severe inundations through their variability. Increasing understanding of the tide-only inundation is important for measuring the possible impact of changing tidal patterns to additional coinciding sea level rise. (Hague & Taylor, 2021)
Common ways for assessing tidal variability and MSL by the tide are provided through tide gauge data. The calculation of MSL by tidal patterns is dependent on the applied methodology. Furthermore, the comparability of tidal data can be very challenging and causes a wide range of hardly comparable studies. The relative sea level is from much more attention in the field of tidal and overall hazard assessment. This variable can be derived only by measurements and resulting interpolation operations if no in situ data exists. It has to be differentiated if tidal mean data or extreme values are collected and further used for the calculation of extreme events. (Sweet et al., 2020)
Tidal characteristics are the regional strongly affecting variable on the occurrence of extreme water levels near the coast and resulting inundations. The characteristics of occurring tidal patterns and resulting tidal surges are assumed to be also related to regional shelf conditions as shown by Dodet et al. (2019) at the French coast. Also in hydrological terminology different tidal regimes can be identified by comparing different coast types and regions to each other. The main forcing factors for tides are the astronomical variability of the tides and the meteorological variability additional to the astronomical main character. It can be difficult to distinguish between these factors, as they are related to each other and a plain astronomical tide is a scientific reduction, which would be only measurable under ideal conditions without any atmospheric influence. Additional factors on tides are also the shelf structure and oceanic factors as currents. (Dodet et al., 2019)

2.3. Investigation sites

2.3.1. Houston (US)

The coastline of Houston was heavily hit by severe flooding and storm events over the past decades. Some of the storms are well known for their extensive impact on the economy and disasters with thousands of fatalities in the densely populated cities along the Gulf Coast of the sites Texas, Louisiana, Alabama, and Florida. Hurricane Katrina in 2005 for example caused direct damages over 80bn US$ plus rebuilding and economic production costs. A surge database (SURGEDAT) for the complete gulf coast of the southern United States of America collects 195 storm events since 1880 and documents well the history of severe events with high rates of fatalities even under ongoing adaptions for mitigating the risks from these severe events. The most extreme events, which were identified through the data collection process of the database reached up to 8.4m over the highest astronomical tide. Even by neglecting any complex intercorrelation between tide and surge, the atmospheric forced surge heights in the Gulf of Mexico are suitable to cause severe inundation in the future as well. (Needham & Keim, 2012)

In the region, several investigations showed the complex interdependency between landfall timing and tide and the shelf geometry for the characteristics and height of occurring storm surge. (Rego & Li, 2010)

The importance of a suitable regional risk assessment increases due to ongoing sea-level rise. Simulations for the northern part of the Gulf Coast led to a possible increase of the inundated areas up to 87% resulting from storm surges under the condition of a rising sea level. Non-linear additional changes up to 1m by surges under sea-level rise conditions could accelerate the possible occurrence of heavy inundation events and extreme water heights at the shoreline due to storm events. (Bilskie et al., 2016)

As the region of the Gulf of Mexico coast of the United States is characterized by bays and agglomerated and densely populated, the investigation also aimed at the changing conditions there. Changing conditions in the bay areas are more likely to induce inundation events directly in the agglomerated regions. Passeri et al. (2016) simulated tidal amplitudes especially in the bays and revealed possibly increasing tidal amplitudes up to 67% and faster tidal propagation.

This investigation results are similar to other regional studies and draw a picture of coinciding feedback loops for increased flooding risk in the overall area of the coastline at the Gulf of Mexico, especially in areas that are exposed frequently to severe tropical storms like Houston or New Orleans.

Inundation modeling in the region of Galveston (Texas) is not easy, because of already made adaption on flooding risks from expectable and historically measured events. This adaption in form of dikes and defense structures build for example by the Federal Emergency Management Agency (FEMA) or the U.S. Army Corps of Engineers is calibrated by 100 to 500 years return period events. This mostly backward directed perspective could be assumed as not suitable anymore if the main driving parameters and forcing factors are changing in a way, that it is even not applicable to extrapolate certain trends and return periods from historical data. (Lickley et al., 2014)

Additionally, the historical data regarding surge-inducing storms is in some kind not so useful at all, because of the lack of continuous and comparable data and the future shift in the exceedance probabilities of wind speeds and resulting surges, landfall timing, and track direction. Therefore as Lickley et al. (2014) points out, the Global Circulation Models (GCM) are used to simulate future forcing factors for storms and the resulting storm occurrence to model the hydrological consequences.

Especially the lack of suitable storm data could be explained with the extensive need for space-borne data for estimating the parameters like storm track direction and identifying the timing and basin of their origin.

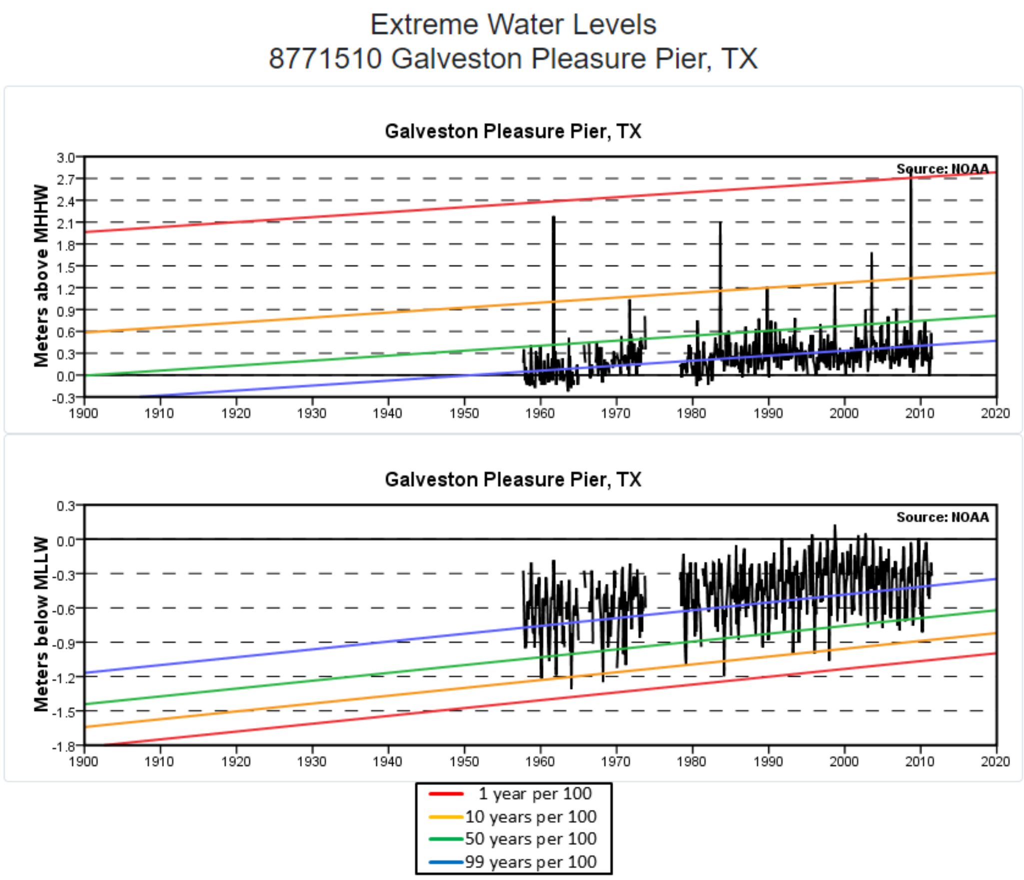


Figure 2: «The monthly extreme water levels include a Mean Sea Level (MSL) trend of 6.84 millimeters/year with a 95% confidence interval of +/- 0.81 millimeters/year based on monthly MSL data from 1957 to 2006 which is equivalent to a change of 2.24 feet in 100 years.« https://tidesandcurrents.noaa.gov/est/est_station.shtml?stnid=8771510

The National Oceanic and Atmospheric Administration (NOAA) is assuming an increasing probability of extreme water level threshold exceedance and increasing extreme water levels. Figure 2 shows an example from Galveston at the shoreline to the open ocean and the historical tendency between 1900 and 2000 assuming a constant sea-level rise. The probability of occurrence is typically expressed by the return period (RP).

More detailed information about the shelf geometry and characteristics near the coast of Galveston/Houston can be accessed in Annex 2. The map shows clearly a relatively shallow geometry in the region, which differentiates it from the Sydney (AUS) investigation site.

2.3.2. Sydney (AUS)

Sydney is a city in south-east Australia in the most populated state of New South Wales. In the last decades, an extensive change in the population density in the coastal regions took place, which intensifies the need for more research about the exposure of the region towards coastal food events. (Wainwright et al., 2014)

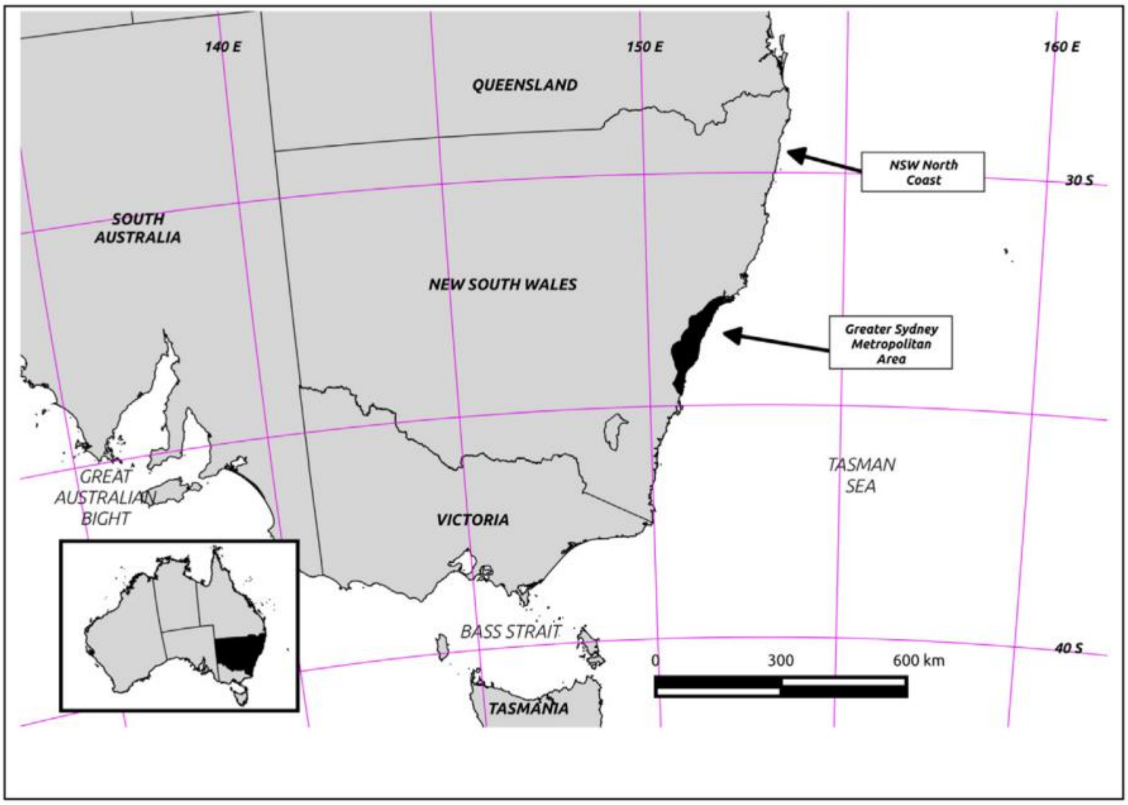


Figure 3: South Eastern Australian and New South Wales (Wainwright et al., 2014)

Rough estimations for a 1.1-meter sea-level rise change in the future resulting in 40000-60000 residential buildings affected when coinciding with extreme storm events. Next to sea-level rise change also interdecadal variabilities as El Nino and Southern Oscillation are forcing factors for coastal erosion processes in this region. (Wainwright et al., 2014)

Dall'Osso et al. (2014) compared multiple hydrological perils and their possible impact in Sydney. The results suggest a higher impact by storm surges in the rank of hydrological perils than caused by tsunamis.

The impact from El Nino and the reverse phenomenon La Nina decreases with increasing distance from Darwin and is more represented in the northern coastal part of Australia. Even complex are the tidal pattern varying on different time scales along the coastline. Next to diurnal and semi-diurnal amplifications, there are also interannual variabilities that must be considered carefully while estimating the possible extremes and their probability of occurrence or the probability of exceedance of certain thresholds. Important is the observation of

similarly varying tidal patterns of daily mean tides and highest astronomical tides for the choice of the used parameter and possible model robustness towards any modeled extreme value. (McInnes et al., 2016)
According to Walsh et al. (2016), Australia is affected by different storm events, which can cause also coastal extreme conditions depending on the area. Tropical cyclones, known for the most severe storm surges at coastlines all over the world, are occurring only approximately down to the 27˚S latitude. In the case of ongoing global warming, there can be assumed, that there will be also a tropical cyclone south of the 27˚S latitude at the Australian coast, which would also affect the coast of New South Wales. Currently, areas south of the 27˚S latitude are more likely to be hit by events of synoptic scope. These are events from larger scales like the East Coast Low (ECL) with also potentially high occurring wind speeds and surges. (Walsh et al., 2016)
A study about the impact of storms on extreme water levels considering extratropical and tropical storms shows the immense difference of expected heights between the storm types. Tropical storms are much more likely to induce the most extreme water levels with up to 3 meters in northeast Australia while coinciding with high tides and a simulated 1000 year return period cyclone. In comparison, the results of the study expect extreme water heights of less than 1 meter induced by extratropical storms in southeast Australia. (Haigh et al., 2014)
McInnes et al. (2013) assume a higher contribution of the ongoing sea-level rise to extreme water heights by the factor of 2 in southeast Australia in comparison to the effect of peak wind speeds on the total water levels in the future.
Stating this, it has to be considered carefully, that it only means the possibly occurring contribution to increasing water heights and not the likelihood of storms in the region at all.
A1 shows the investigation site definition and the regional bathymetry.

3. Method

3.1. Data

In the following chapter, the used datasets are. All documentations of the datasets by their academic institutions are referenced and outlined. If operations are applied initially on the data by choosing or extracting the data, it will also be mentioned in this chapter for increasing transparency.

3.1.1. Tides

The highest astronomical tides are derived from the Finite Element Solution 2014 (FES2014) dataset by Vousdoukas et al. (2018). By them, it is declared as a spring tide. Due to the inaccurate definition of spring tide, the term highest astronomical tide (HAT) is used, which approximately occurs twice every lunar month. Probability density function (PDF) is also provided and 1980-2014 is the baseline for their calculations. Provided data is derived from the FES2014 tidal cycle data by extracting the high tide of each tidal cycle. (Vousdoukas et al., 2018)

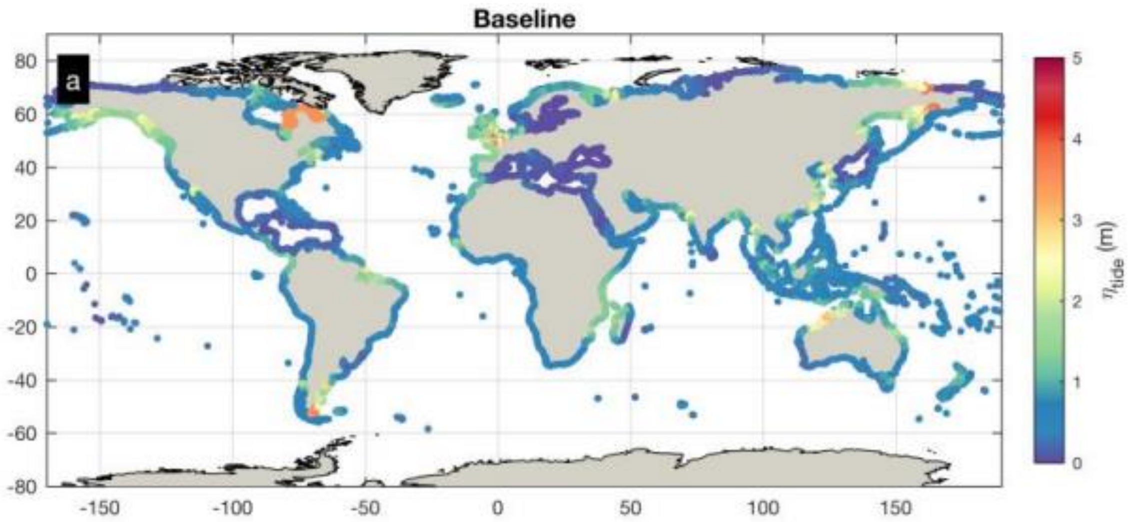


Figure 4: Highest Astronomical Tide (HAT) in meter (Vousdoukas et al., 2018)

Finite Element Solution (FES2014) global ocean tidal atlas is provided by the French space agency (CNES) and accessible through Aviso+. Significant increases in quality compared to former products were possible because hydrodynamic and ensemble data assimilation techniques were applied. (Lyard et al., 2020)

According to the main equation of Vousdoukas et al. (2018), the tidal data is intended to be used for modeling over MSL. This means, that there is a significant difference between institutions like NOAA which assigns the tidal data normally to the national datum epoch and vertically over mean lower low water (MLLW).

This circumstance is very important, as the tidal data could not be used with other data assigned on MLLW because this would lead to an incomparable data issue.

In comparison to vertically MLLW assigned tidal data, the MSL assigned data is lower but overall not comparable.
An uncleared issue could be the different definitions of the MSL for the tidal data and other used data. This eventually leads to uncertainty and an expectable but not proven offset.
The diagrams in A2 show the difference between the stations considered at the investigation sites and the height of the HAT median, 5^{th} and 95^{th} quantile. This illustrated clearly the difference between the investigation sites and the tidal baseline.

3.1.2. Sea level rise

The sea-level rise data used is based on the scientific foundation outlined by Pörtnere et al. (2019) in the SROCC published in 2019.
Projections of sea-level rise change are based on three main processes: thermal expansion by warming of the oceans, changes in inland stored water and melting of polar ice shields and glaciers. Development dependent on these factors is mostly connected to the applied RCP scenario and how the impact might be on one of the factors. This uncertainty is mainly based on the problem of connecting carbon dioxide concentration of the mid-Pliocene Warm Period (mPWP) and before to temperature changes, because the application of ice core techniques is not applicable for these periods that far in the past. Substitute techniques are applied and researched for increasing confidence about the carbon dioxide concentration and temperature in these times and derive implications to today's development.
The instability of the ice shields is also uncertain. A collapse could force a much faster sea-level rise than no expectable. Within the scenarios applied on the data production, this factor is not considered for calculating the time series of rising sea levels. GMSL change is not likely to be representative for every region, because of relative changes up to 30% due to regional effects like land ice loss and ocean dynamics. (Pörtnere et al., 2019)
Because of this fact, relative sea-level rise data was composed for assessing globally, but regional differentiating RSLR.

Calculation of the sea level rise data is based on the implication before and provides global raster data sets with RSLR data and further statistical parameters. Median, $5^{th,}$ and 95^{th} percentile yearly RLSR as global raster sets for the years 2007 to 2100 and the RCP scenarios 2.6, 4.5, and 8.5 were provided and are most important for this work. The diagrams in A3 show the median sea-level rise values in the time series at the two investigation sites. (Oppenheimer et al., 2019)

The data was accessed through the data portal of the European Environmental Agency data portal (https://www.eea.europa.eu/data-and-maps/data/external-/ipcc-srocc-data-on-sea accessed 09.2021).

Regarding the alignment of the SROCC projected sea-level rise data, the SROCC data is broadly consistent with the newly modeled data of AR6, despite updates of the models and methods applied. So even if SROCC is not the most recent publication there, it is quite reasonable still to use the data. (Arias et al., 2021)

3.1.3. Non-tidal residuals (NTR)

It is difficult to approach a reasonable way for higher water levels caused by atmospheric forcing. There are several ways for modeling datasets for this occurrence, but most of them already incorporate tidal amplifications. The need for a dataset, which addresses only the residuals identified to occur within meteorological events and caused only by storms and not by the oceanic base variability is given, because of the intended modeling approach for the total water level calculation. The so-called non-tidal residuals, can be roughly defined as an offset on the tide and mean sea level caused by atmospheric forcing during storm events.

The work of Tadesse & Wahl (2021) provides a database of reconstructed non-tidal residuals under consideration of five different global circulation models (GCM) for modeling atmospheric forcing. The reconstruction databases cover daily maximum surge values from the five GCMs and different periods and are validated against extreme water levels from the Global Extreme Sea Level Analysis (GESLA-2) database. For the modeling 882 tide gauge stations are used and the longest reconstructed storm surge period is the year 1836.

The non-tidal residuals are extracted by removing the tidal signal from the storm surge values. Tidal signals were generated by a harmonic tidal analysis and the results were recalculated to hourly sea level by detrending. Maximum daily values were extracted from the calculated non-tidal residuals for each respective period of the GCM in use. (Tadesse & Wahl, 2021)
It is questionable if tidal detrended data can be removed to generate the possible offset. It insists on an existing understanding of the generation of the total water level and the approximation of the contribution of tide and storm surge to the measured water level of the validation dataset. This precondition is partly addressed in this thesis, so the possibly occurring bias is documented and might be discussable.

3.1.4. Bathymetry

Bathymetric data is used for getting a better understanding of the investigation sites and the shelf geometry. Even if the bathymetry will not be considered in the modeling process of the additive model actively, the understanding of the shelf environment of the investigation side could lead to a better understanding of the modeled data and the input parameters. The data is also used for the more complex models incorporating the individual characteristics of the investigation sites and relative water depth changes. For this model, water depth is derived from the bathymetry as an approximate variable.
The GEBCO dataset is used in A1 for introducing the investigation sites with their near-shore water depths.
The GEBCO 2021 grid is a joint project embedded into the Nippon Foundation-GEBCO Seabed 2030 Project (https://seabed2030.org/resources-journalists). The dataset provides a 15 arc-second interval grid global coverage and under the contribution of several data providers (https://www.gebco.net/about-_us/acknowledgements/our_data_contributors/).

3.2. Modeling of total water levels (TWL)

3.2.1. Overview and data preparation

The intention of the modeling is the calculation of near-shore water heights occurring at coinciding of high tides, average atmospheric conditions (represented by non-tidal residuals), and sea-level rise for providing a suitable input for further inundation modeling onshore. As the target variable, which is calculated, the total water level (TWL) is chosen as a combination of the coinciding coastal hydrological parameters. Dependent on the model approach, different combinations can be used for calculating the height of the total water level. A detailed description of the chosen combination of the parameters will be given in the model methodology sections 3.2.2. and 3.2.3.

In further part 5 of the thesis, it will be discussed, how the total water level calculation is working well under the precondition of the chosen parameters and the chosen calculation approach. Integrated into the modeling, the question of the climate change-driven influence of changing sea level is addressed by projecting the base approach into the future with the sea level rise data. Due to extensive uncertainties, it is declined to use even climate projected hypothetical shift of meteorological conditions.

For the modeling, the data sets are described in 3.1.1. to 3.1.3. are prepared in different ways for evaluating their usability and meaning. The methodological process can be divided into 4 main steps. First, the data is pre-processed and explored statistically, and tested regarding their suitability for the intended model purpose. Not all of the data is given in continuous spatial data. Most of the data is delivered in form of point station data. In the second step, after the pre-processing, a first additive model is introduced to assess the simplest approach, on which the non-additive approach should be based. Hardly to divide from the first steps is the spatial integration and application of the models. It will be described as a separated model step because the spatial operations are slightly different in their overall logic in comparison to the model construction before. To connect the intended model workflow with the model landscape overview, in the beginning, the spatial integration is analog to the application of the Eulerian model type.

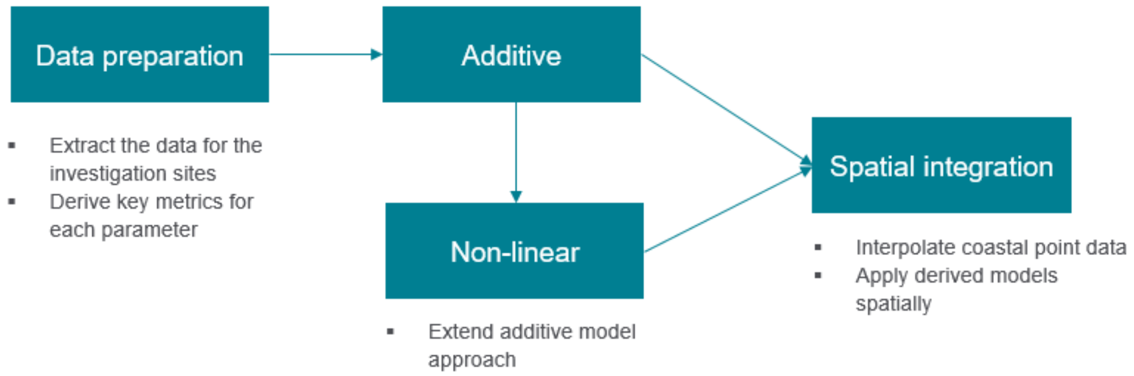


Figure 5: Modelling workflow overview

As outlined before, water levels near the coast are primarily influenced by different parameters as atmospheric and astronomical tide variation (Dodet et al., 2019). For a sharp differentiation between the parameters and their meaning in the following part, it will briefly be described, how they are defined from the scientific side, how they are derived statistically, and then used in the following model construction part.

The astronomical tide is the gravitationally induced base variability of sea level and can be described as a used baseline. The astronomical tide maximum is consequently the highest occurring water level in the theoretical situation of no atmospheric forcing or influence. In contrast to the astronomical tide, the atmospheric tide is the tidal variability under consideration of atmospheric or meteorological influence like occurring storms. (Haigh, 2017)

Representative for the highest astronomical tides, data from Vousdoukas et al. (2018) is chosen. The available data set already contains the HAT maximum values and the background of the data is described in 3.1.1.

The original data provides three statistical figures for each station, which can be accessed through A2. A9 shows the selected stations at the investigation sites and A10 the detailed locations of each station. To realize further calculation with the data connected to the other datasets, the point data is interpolated with an inverse distance algorithm and rasterized to a cell size of 0,005.

Additionally, sea-level rise adds relatively constant height to this variability, which is also influenced by shelf characteristics on a local and regional scale.

These mentioned parameters and the assumption of their contribution to total water heights near the coast – excluding direct run-up space at the direct

coastline or beaches – are the foundation of the model approaches worked out in the following sections.
Dodet et al. (2019) also mention oceanic influences as currents and swells, which will not be considered directly in the model itself, because of the uncertain suitability of the intended eulerian approach for incorporating dynamic ocean processes on different scales. Currents and swells can be incorporated by using datasets, which are based on dynamic models. Dataset specifications are outlined in detail in the data section (3.1.1-3.1.4).
Sea level rise data of the IPCC data commonly face the lack of higher resolutions. The corresponding cell size of the sea level rise data is 1 in comparison to 0,005 of the data of the other two variables. Original relative sea-level rise data from IPCC is derived from the time series for the projected years 2050 and 2100. As a mostly robust statistical figure, it is decided, to use the median of the respective years for the calculations. Due to projection issues, the data was corrected by adding 90 degrees to the latitude to reach consistency with the other data. The correction was provided with a workaround by creating a consistent point layer from the original raster, changing the latitude coordinates, and rasterizing it again. Additional validation is performed to ensure the (spatial) consistency with the original data. Additionally, the sea level rise data is interpolated with a standard inverse distance weighting interpolation for approaching every point near the coast.
Non-tidal residuals data pre-processing is mostly driven by the goal of providing return periods and the workaround to reach that. This approach aims at finding a workaround for other data, which could make the overall model more modular.
First, the stations within or around the investigation sites were identified and extracted. For assessing the statistics of the time series the over 17 million values were brought into a SQL-based database. Chosen stations can be seen on the maps in A8. Yearly mean and median values were also derived from the daily maxima of each times series to compare possible non-expected distribution in the data. Broad convergency of mean and median overall models and time series suggested the use of an approach based on the Weibull formula.
Because of the extensive usage of the Weibull distribution for calculating return periods for meteorologically associated events, it is decided to use a simple

calculation approach based on the Weibull distribution. The data of the 20^{th}-century reanalysis (20cr) is chosen as a variable to calculate the return periods, because of the largest temporal extent of the reconstructed values from 1836 to 2015. Calculations were performed by ranking the yearly mean values of the reconstructed daily maxima from low to high and assigning a rank respective from 1 to 180. The following formula based on the Weibull distribution assumption is then used to calculate the exceedance probability of the occurrence of the non-tidal residual.

$$exceedance\ probability = \frac{n - i + 1}{n + 1}$$

where n is the values of the length of the time series (180 years) and i is the assigned rank of the value. The return period is then derived by inverting the calculation by dividing one by the exceedance probability.

Table two shows the derived return periods for 10, 20, and 90.5 years. Because of the use of yearly mean values, the series length was decreased to 180 years and therefore also the number of return period values was limited. For decreasing further risks of approximative uncertainties, it was decided to use the directly derived return periods for further calculation without any mathematical approximation for identifying 50 or 100 year return periods. The 90.5 return period will be used as a proxy for the formerly intended 100 year return period.

Table 2: Approximately Return Period values given in meters and calculated with the Weibull calculation approach and 20cr

Return Period (RP) in years	**10**	**20**	**90.5**
Freeport	0,101469	0,107337	0,131909
Galveston	0,103538	0,114266	0,136431
Sabine Pass	0,106083	0,110693	0,140317
Fort Denison	0,060039	0,063795	0,068603
Newcastle	0,070064	0,073773	0,077559
Port Kembla	0,044869	0,048517	0,054319

Methodological limitations must be also outlined briefly but will be further discussed dependent to model internal assumptions later in section 5.

The descriptional term of “open boundary” conditions could apply to the model because no dynamical responses from shorelines or bays will be incorporated in the model. The consideration of shelf and boundary responses is connected to currents and quite hard applicable in modeling using spatially discretizing approaches.

3.2.2. Additive model

The first approach follows the assumption, that the different parameters are additive even under changing conditions. That means, that the relation between the parameters is constant while the single parameters could change. In the following given model, only the sea level is changing as a variable, because of the mentioned uncertainties in the modeling of storms, respective non-tidal residuals. Possible changes of the tidal variability or the non-tidal residuals will be investigated in the following section and the evaluation of a non-linear model. The additivity is based on the definitions made by Haigh (2017) for mean sea level, non-tidal residuals, and average tidal amplification. Following that, the MSL rises by RSRL on which the average tidal amplification, represented by the highest astronomical tide and the non-tidal residuals also oscillate.

Hakkou et al. (2019) use an approach, which is in line with these basic assumptions:

$$TWL = \eta + S_s + R_{2\%} + \Delta_{SLR}$$

where

η = predicted astronomical tide

S_s = Storm Surge

$R_{2\%}$ = exceedance wave run-up height

Δ_{SLR} = projected sea-level rise change

This basic formula includes a variable representing the exceedance run-up heights calibrated at 2% for sandy beaches of the investigation site of the specific study.

As described before, the run-up behavior is intentionally not considered in the modeling approach because of the different dynamic and model types. The strong focus of spatial discretization leads not to a meaningful toolset for run-up behavior approximation through integrating a variable as a representation for this dynamic. Overall this dynamic can be described better than a more lagrangian process, rather than an eulerian process type.

Vousdoukas et al. (2018) mainly provide the basis for the additive approach. Their methodology even incorporates changes in MSL through sea-level rise change. The definition of storm surge generated extreme sea levels (ESL) is still not very precise and is therefore in line with other studies which face the problem of very relative and inconsistent definitions through usage of different data, vertical and temporal references.

MSL as reference is a solution for the problem of the vertical reference by assuming a relatively good fit through ongoing approximation of the long-term MSL and similar data sources of a wide range of studies. The obvious possible shortcoming in the usage of similar data sources, institutions, and provided models especially for the simulation of the atmospheric forcing for storm and overall low pressure generated extremes of sea levels, lies in the possibility of an approximated long-term system failure of these studies. These concerns are not significant but should be mentioned for this modeling approach. Increasing the temporal and spatial density of measurements for sea levels and ongoing calibration and validation of models and outputs might mitigate the risks of systematic and further adapted errors.

Vousdoukas et al. (2018) mention the problem of relativity of sea-level changes in their calculations. For the intended model here, the spatial relativity is addressed by using not any global mean sea level change variable, but a spatially differentiated relative sea-level change variable. Its resolution can be roughly described as regional. Details for applying the model spatially are also outlined under 3.2.4. The used variables from Vousdoukas et al. (2018) are η_{tide} and η_{CE}, where η is commonly used for describing an elevation over a reference level (vertical and temporal). So, η_{tide} is the tidal eleveation and η_{CE} is defined as the water fluctuations due to meteorological extremes.

The following basic equation shows the adaption of the equation and the definition of variables of the additive approach. Mainly the so-called meteorological extremes are redefined as non-tidal residuals and the delta of sea-level rise variable described and used by Hakkou et al. (2019) is added:

$$TWL = \eta_{HAT} + \eta_{NTR} + \Delta_{SLR}$$

where

TWL = Total water height

η_{HAT} = highest astronomical tide

η_{NTR} = non-tidal residual with return period ~90.5 years

Δ_{SLR} = Delta of relative sea-level rise to reference level 2007, where relative addresses the spatial non-uniformity based on IPCC data from 2019

The specifications of the user data for the given parameters are given in table 3 below.

Table 3: Description of the data used for the chosen variables for TWL calculation

η_{HAT} Highest Astronomical Tide	Median of derived FES2014 maximum values 1980-2014
η_{NTR} Non-tidal residuals	Non-tidal residual with return period (per Weibull distribution) ~90.5 years of yearly means of reconstructed daily maxima 1836-2015 with 20th-century reanalysis (20cr)
Δ_{SLR} Delta of Relative Sea Revel Rise	Median change values for the given year relative to the reference start year of the time series data 2007

For being more precise the formula must be read vertically like:

$$TWL_{AM} = MSL + \eta_{tide} + \eta_{NTR} + \Delta_{SLR}$$

where

MSL = Mean Sea Level as the vertical reference level

So, the approach is based on mean sea level, which leads to important implications for the usage for further modeling like inundation extent modeling.

As a set of variables, the formula bases also on a very important assumption, that atmospheric forcing is likely to coincide with the highest astronomical tide or, that atmospheric forcing events for creating the maxima of non-tidal residuals last at least so long, that the highest astronomical tide is very likely to coincide with it. The relative sea-level rise is just added to the mean sea level and increasing the overall height of this just additive relation.

3.2.3. Non-linear model

Addressing the question of a possible parametrical approach for approximating the non-linearity of the relation of the given parameters of the additive model needs more defined borders and well-defined assumptions for setting up a model. To approach the relation, system dynamic thinking, as described in the model introduction part, is applied and the information is derived mainly from studies about the relation of the parameters.

The main source of the approach is Arns et al. (2015) and the related assumptions.

The additive approach is based on the set of assumptions, that the sea-level rise does not affect the tidal characteristic or the setup of storm surge. It even assumes, that no spatial difference between the relation of the parameters exists. This simplification could lead to significant distortion for assessing possible total water heights, especially regarding the influence of sea-level rise on tides and the non-tidal residuals.

A more extended approach is suggested to incorporate even the difference between more shallow and tidal driven areas and the possible different influence of sea-level rise.

Mainly two mechanisms are not considered, which are discussed regularly in water level interactions in the additive model. First, the rising sea level possibly increases the occurring total water heights more than the $\Delta RLSR$ through non-linear influence on tidal constituents. Second, a negative feedback loop or mechanism is reducing water heights through decreased bottom friction by increased water depths primarily in shallower waters. Overall the effect of a non-linear increase of tidal constituents seems to be higher than the reduction of the surge heights by decreased bottom friction. A problem occurs when it comes to the exact intensity of non-linear influence on the tidal level. Arns et al. (2015) observed higher positive residuals in areas with higher relative depth changes by also identifying some exceptions. The relative depth changes would be mostly in areas with very shallow water, where tidal components are not that large naturally, but surge events at extreme events very high through intense bottom friction. (Arns et al., 2015)

Due to the obvious problem of the relativity of water depths and its estimation, it is decided to integrate the water depth and possible change through the hydrologically changed residuals as variables into the equation to show this possible relation. The water depth variable is z as estimated water depth referencing Doxani et al. (2012) and the discussed limitations of this variable.
A first approach to take this relationship into account, by aiming only on the positive residuals caused by the non-additive influence on the tide, is accessible with the following equation:

$$TWL_{STMR} = \left(1 + \frac{\Delta_{SLR}}{z}\right) \times \eta_{HAT} + \Delta_{SLR} + \eta_{NTR}$$

The water depth approximation z is also given in meters as the other values. This equation refers to the observation of the study by Arns et al. (2015), that the larger the change of the sea level compared to the water depth, the larger the residual. The approach has low empirical evidence about the strength of this assumed relation between $\Delta RSLR$ and the other parameters. The equation just provide a general weighting by factoring the $\Delta RSLR$ higher at minor water depths.
Another limitation is the assumed linearity and proportionality of the influence of the relative depth because it could be stated for instance, that this effect is limited to shallow water only. The difference of influence dependent on different water depths on the parameters is described for instance by Dodet et al. (2019). This model only addresses the first influence of sea-level rise on the tide. This approach can be also seen as a simple base model, for considering different tidal conditions, following the hypothesis of a strong positive correlation between shallow shelf characteristics and micro-tidal conditions and deeper waters near the shoreline and macro-tidal conditions.
The next relation is the behavior of surge residuals or non-tidal residuals under changing tidal patterns. Arns et al. (2015) also mentioned possible interpretable negative feedback loops from increasing water depth through higher tides and resulting in less bottom friction. This could decrease the build-up of non-tidal residuals and extreme residuals like storm surges.

$$TWL_{STM} = \left(1 + \frac{\Delta_{SLR}}{z}\right) \times \eta_{HAT} + \Delta_{SLR}$$

Where TWL_{STM} defines the relative change of the MSL through SLR and its proportionally assumed influence on the HAT. This change in water height is interpreted as an influencing factor to lower surges by increasing friction. This relation is also assumed as simply proportional:

$$TWL_{adjNTR} = \left(\frac{z}{TWL_{STM} + z}\right) \times \eta_{NTR}$$

Where $AdjNTR$ stands for the adjusted non-tidal residual considering less friction by the setup through SLR and its influence on tides. The given formula gives the overall SLR-driven water depth a reverse relation for weighting the NTR. That means, that the higher the positive residual to the approximately given “normal” bathymetry, the lower the NTR.

And the final TWL is then calculated as $TWL_{STMadjR}$ as follows:

$$TWL_{STMadjR} = TWL_{STM} + TWL_{adjNTR}$$

There are also concerns about the evaluated kind of model before. The global investigation by Idier et al. (2019) advises against any usage of relations on a global scale by showing significant regional differences and incoherence in the magnitude and direction of the effect from -15% to +15% of the $\Delta RLSR$ on the increase of the tidal range. More evidence about the regional complexity is given by Pickering et al. (2017), because of the possible influence on different tidal constituents, which increase and even decrease the tidal response on the sea-level rise without giving any generalizable effect, because of opposing results and non-proportionality between sea-level rise and the tidal responses. It is assumed that the evenly observed possible occurring negative residuals induced by the sea-level rise on tide could result from phase shifts between specific tidal constituents. (Pickering et al., 2017)

Because of the increasingly dense evidence of the influence of sea-level rise on the change of the tidal pattern, it is decided to define a range of possible influences derived from the collection of Idier et al. (2019).

To take the limitation made by Idier et al. (2019) into account, a simple calculation is made, which assumes that the ±15% of sea-level rise is not exceeded on the tidal amplification, which gives a range of possible occurring values. The non-additive model will then be compared with this threshold range in the tidal amplification.

$$TWL_{STMT}\{a \dots b\} = \pm(0.15 \times \Delta_{SLR}) + \eta_{HAT} + \Delta_{SLR} + \eta_{NTR}$$

Where a represents the lower boundary with -15% of sea-level rise on the tidal amplification and b the +15% boundary.

The equation also interprets Idier et al. (2019) that the sea level rises tidal amplification additionally to the rise of MSL. Idier et al. (2019) show, that under uniform sea-level scenarios significant differences in sea level-induced changes of tides occur. Also, no general specification is derivable based on this study, which results in the general threshold solution suggested above for defining possible value ranges for this interaction.

For providing a better overview the following table 4 shows the evaluated models, the assigned names and abbreviations, and the formulas.

Table 4: Methodological model overview - formulas

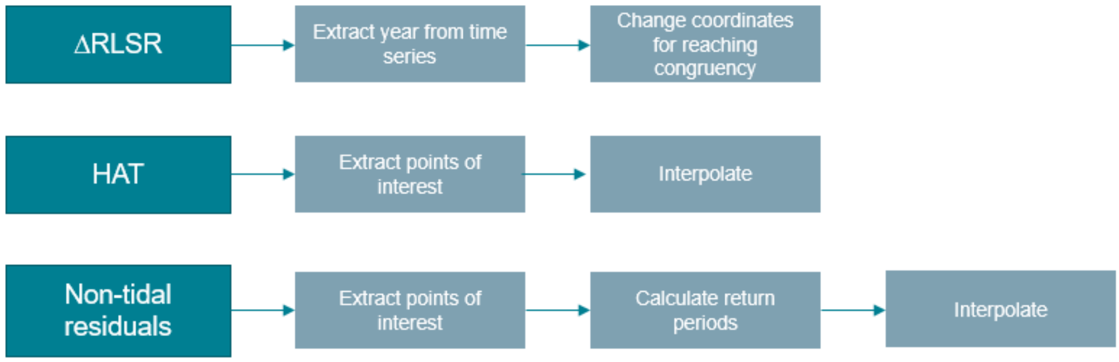
Model name	Abbr.	Formula
Additive **m**odel	**AM**	$TWL_{AM} = MSL + \eta_{tide} + \eta_{NTR} + \Delta_{SLR}$
SLR-**t**ide simple relation **m**odel	**STM**	$TWL_{STM} = \left(1 + \frac{\Delta_{SLR}}{z}\right) \times \eta_{HAT} + \Delta_{SLR}$
SLR-**t**ide simple relations **m**odel with **t**hresholds	**STMT**	$TWL\{a \dots b\} = \pm(0.15 \times \Delta_{SLR}) + \eta_{HAT} + \Delta_{SLR} + \eta_{NTR}$
SLR-**t**ide **m**odel with non-tidal **r**esiduals added	**STMR**	$TWL_{STMR} = \left(1 + \frac{\Delta_{SLR}}{z}\right) \times \eta_{HAT} + \Delta_{SLR} + \eta_{NTR}$
Adjusted **n**on-**t**idal **r**esiduals	**AdjNTR**	$TWL_{adjNTR} = \left(\frac{z}{\eta\Delta_{SLR} + z}\right) \times \eta_{NTR}$
SLR-**t**ide **m**odel with **adj**usted non-tidal **r**esiduals	**STMadjR**	$TWL_{STMadjR} = TWL_{STM} + TWL_{adjNTR}$

3.2.4. Spatial integration of the extracted relation

In the next point, the spatial realization of the intended approach is described. The data was prepared as described in the preparation part. On that basis, simple raster-based map algebra expressions are used to apply the derived relation between the variables, represented by the raster datasets.

The following diagram provides an overview of the applied operations.

Table 5: Spatial data preparation for each variable



There are some points, where some shortcomings of the data could be seen regarding their different resolution. Especially the sea level rise data by IPCC is provided in much lower spatial resolution naturally than the interpolated, point location-based data for the non-tidal residuals and the tides. For transparency reasons, it is marked, that the given spatial resolution through the interpolation is also questionable under consideration of the scarce number of provided points. Nevertheless, it was decided to decline a resampling of the sea level rise data for increasing the spatial resolution and for providing a smoother, more consistent appearance of the model output. The question of different resolutions and overall rasterized hydrological data points to the problem of discretized model approaches for hydrological modeling and their static character. This will be addressed in the discussion of the model approach.

Another point is the different extent of the raster dataset for each variable in the investigation sites. Because of the statistically derived information of the datasets for non-tidal residuals with its return period assigned data and the HAT, both based on point location data, the spatial realization of the relation (respective spatial integration) is done with the smallest extent of the data, which is non-tidal residuals for the Houston site and HAT for the Sydney site.

For reasons of better transparency and as simplification it is waived to increase any consistencies in the extent of the data in the investigation site or the spatial resolution.
Estimating the total water heights through spatially integrating the derived relation of the chosen hydrological parameters is done along the coastline between very shallow waters and the deep ocean referring for example to Woodworth et al. (2019), which stated different characteristics of occurring total water heights between the deep ocean and more shallow waters. Additionally, only this space is relevant for possible further usage of the data for inundation extent estimation. The intention is not to model mostly lagrangian and dynamical conditions in the shallow water areas, because they provide different challenges mostly related to the direct runoff behavior on micro scales, which gives them insight into the expected interaction with the coastline and possibly resulting inundation.
In shallow waters, other parameters as sea flow movement, sediment transport, and dynamic of currents and swells are more important in this area to derive effects on the inundation and interaction with the shoreline. (Røed, 2019)
The choice for modeling is made to the area between littoral and shallow water, not necessarily permanent inundated and highly affected by river estuaries and detailed geological and bathymetrical conditions, and the continental shelf break. Next to the preconditions, that only data near the coast is considered, it is not considered the assumption from Weaver & Slinn (2010), who state, that the influence of bathymetric characteristics – which need to be addressed with higher resolution data – starts to decrease between 25-40m water depths.
The overall methodological approach could be described as open boundary condition vertical (regarding bathymetry) and horizontal (regarding shoreline types, bights, and basins).

4. Results

4.1. Additive model

The additive model results in constant changes driven by the sea level rise as a variable, which is changing only. The mean total water levels driven by these sea-level changes are documented in table 3 below.

Table 3: Total water heights (TWL) additive relation mean of the result rasters

Sydney

	2007	2050	2100
RCP 2.6	0,713596362	0,94383	1,165143
RCP 4.5	0,713596362	0,96949	1,304876
RCP 8.5	0,713596362	1,004424	1,643811

Houston

	2007	2050	2100
RCP 2.6	0,384464646	0,651864	0,857902
RCP 4.5	0,384464646	0,648631	0,969414
RCP 8.5	0,384464646	0,682402	1,267594

Table 3 shows the mean values of the result datasets in the RCP scenarios and the projection time point. The values are the TWL values, which means the elevation of water over the MSL under coinciding conditions of the variables in use. It is accessible, that analog to the RSLR data the RCP8.5 scenario at the projection point 2100 leads to the highest total water level under the given conditions of the highest astronomical tide and a 90.5 year RP daily maximum and yearly averaged non-tidal residual of the time-series of the 20cr data.
The expected spatially relative sea-level rise in this region is higher and leads to overall higher values at the Sydney site.
Due to the naturally spatial character of the data, the spatial mean values are limited regarding their degree of delivered information about the result. Technically correct, the mean is the mean of all cell values of the given result raster. Because of the usage of interpolated datasets, data on and beyond the coastline was not excluded for the calculation of the mean values.

It has to be mentioned, that 2007 is just provided as a reference example within this model set up and used data. In 2007 there is no SLR because it is used as a reference point or baseline.

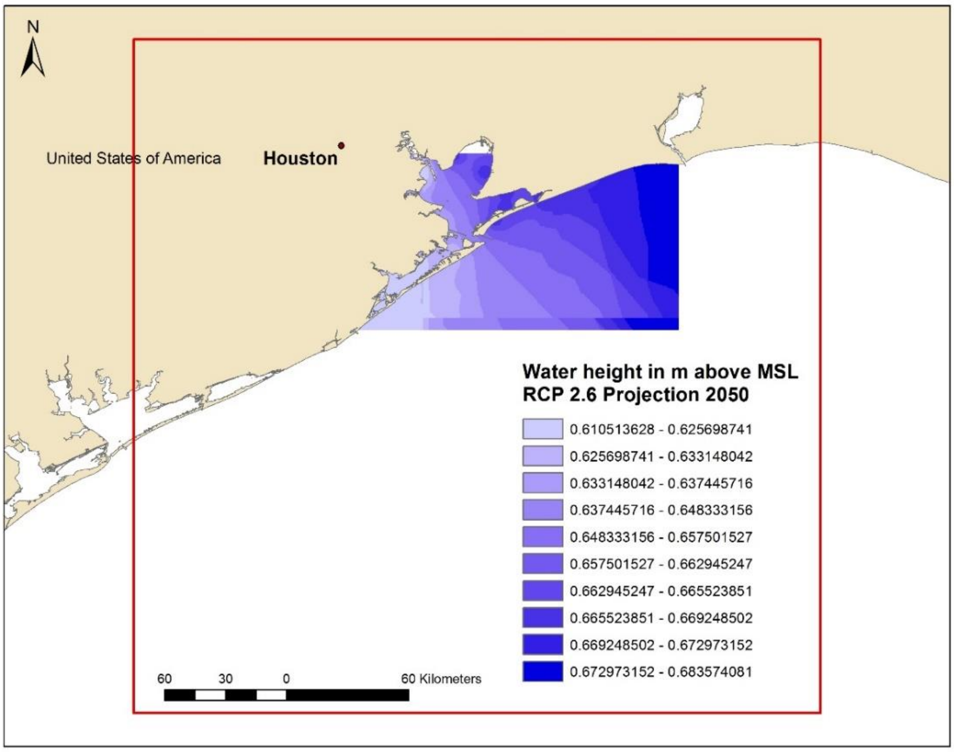


Figure 6: Houston additive model result RCP2.6 2050

Spatially, the data shows the highest total water heights equivalent to the baseline with sea-level rise in respect to the projection year and emission scenario added. In Houston, the highest water heights can be observed in the eastern part of the plot. The non-spatial sea level rise mean increase can be seen in A3.

A11 shows categorial maps for assessing the overall change through the different projections and emission scenarios. As expected, even equivalent to A3 the highest total water levels can be observed in the RCP scenario 8.5 at the projection for 2100.

At the investigation site Sydney, similar observations can be made, as it is also equivalent to the SLR development. The highest total water heights can be seen in the northern part of the site.

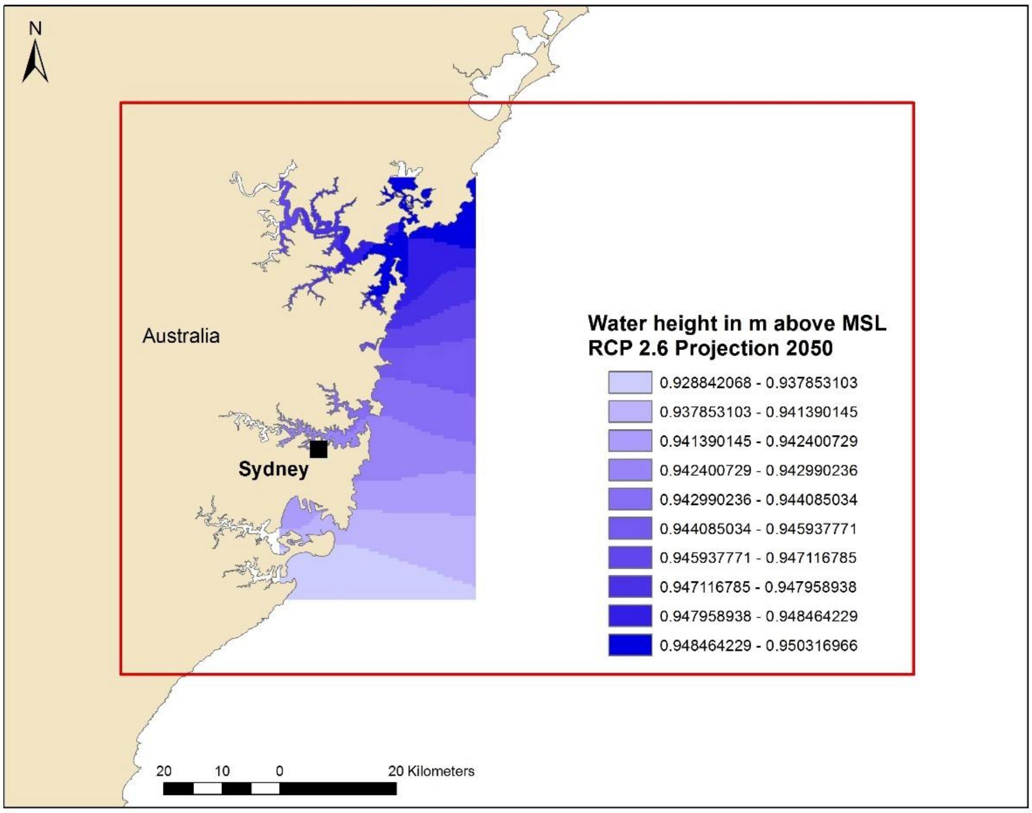


Figure 7: Additive model result in Sydney RCP 2.6 2050

A12 shows the Sydney site and all of the categorial maps for assessing the changes.

The overall existing disparity of the values relative to the value range at both sites shows the limited degree of information of the mean values of the rasters. Nonetheless, the value range is not that large (A14), so the mean can give information for the assessment of the general trend of the result rasters. The additive development can be seen in A13 in two diagrams.

4.2. Non-additive model

For the presentation of the non-additive relation, a selection is made considering STMR, the finally combines STMadjR and a comparison of these results to STMT as threshold calculation. This selection is mainly made, to decrease the extent of the result presentation to the data, which is needed to verify and discuss the primary questions of the investigation. All other data which was processed was also investigated on possible contrary indications or affections on the discussion of the primary questions.

4.2.1. STMR

STMR is presented for showing the difference between the application of the relative tide increasing influence of sea-level rise under the assumption of no influence on the non-tidal residuals.

As before, the result presentation has to be made spatially and non-spatially. For this, the minimum, maximum, and mean values of the spatial mean of the raster data. At the additive model, this data was able to give more information, because of the relatively uniform changing sea level rise per scenario and projection. Indeed, the STMR and STMadjR results are expected to be less uniform and the biggest changes are expected in the spatial distribution of the results.

The mean values of STMR for both sides are only changing slightly as can be seen in A15. On the other hand, the value range of the raster increased significantly in comparison to the additive relation. Especially the maxima increasing in RCP 8.5 massively (A5). Further interpretations regarding this development will be made in the discussion in chapter 5.1.

STMR RCP 4.5 2100 Houston

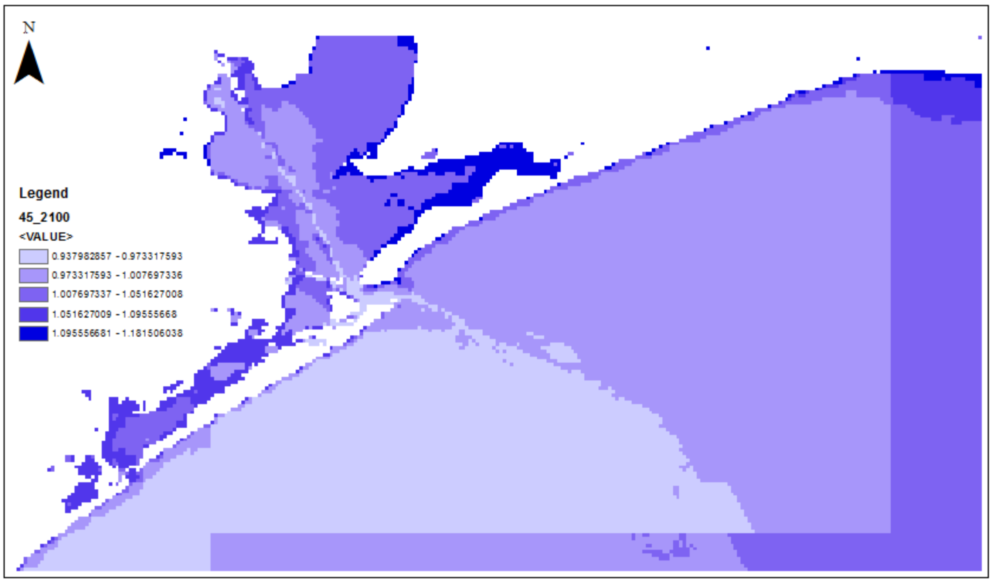


Figure 8: STMR RCP 4.5 Houston

The appearance of the result rasters of STMR is slightly different, as the usage of no-data fields for every field without water depth (which is then assumed to be onshore). All following figures for assessing the results of the calculations are without any topologic information and the coastline. The data shows the calculated offshore plots only. Coastline at the Houston plot and Houston bay is at the northern end of the presented data naturally and western at the Sydney site. Lateral or not connected raster cells are a result of the modeling.

Figure 8 shows the Houston site with RCP 4.5 at 2100. It can be observed, that the highest values occur beyond the open ocean and near the coast.

Also at the Sydney site in figure 9, this effect can be observed.

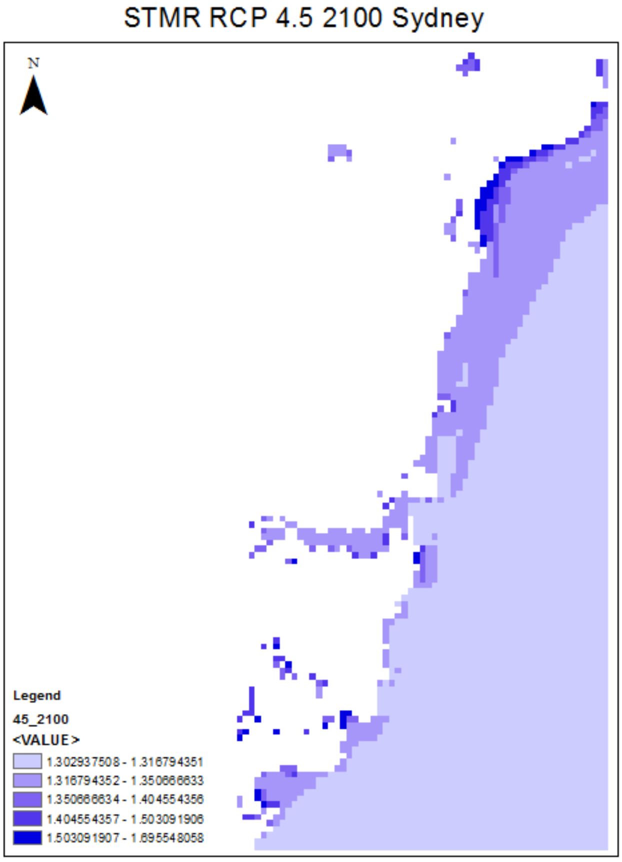


Figure 9: STMR RCP 4.5 Sydney

4.2.2. STMadjR

STMadjR includes the potentially lowering effect of increasing water depth through the approximative use of the bathymetric data. This leads to the observation of lower spatial mean maxima of the result datasets. The mean values of the spatial mean in Houston are overall more decreased than in Sydney in comparison to the STMR results. This observation will be important for the discussion. Spatially the observations are consistent with the STMR results with the slight differences in the value range and mean maxima.

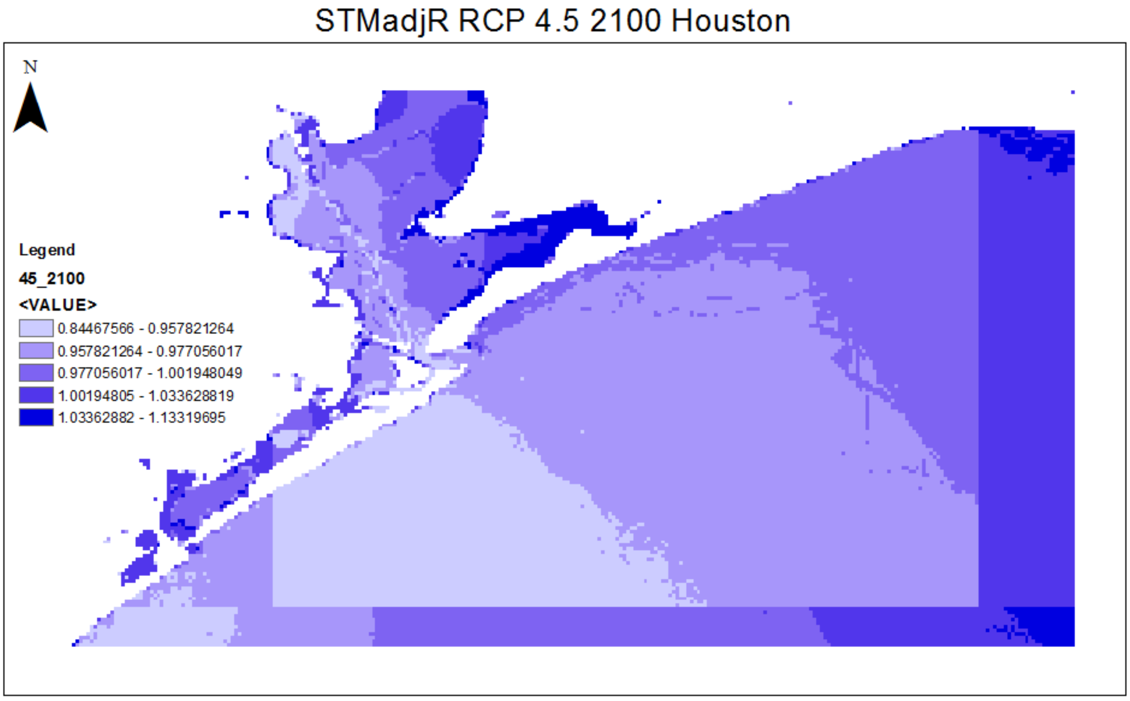


Figure 10: STMadjR RCP 4.5 Houston

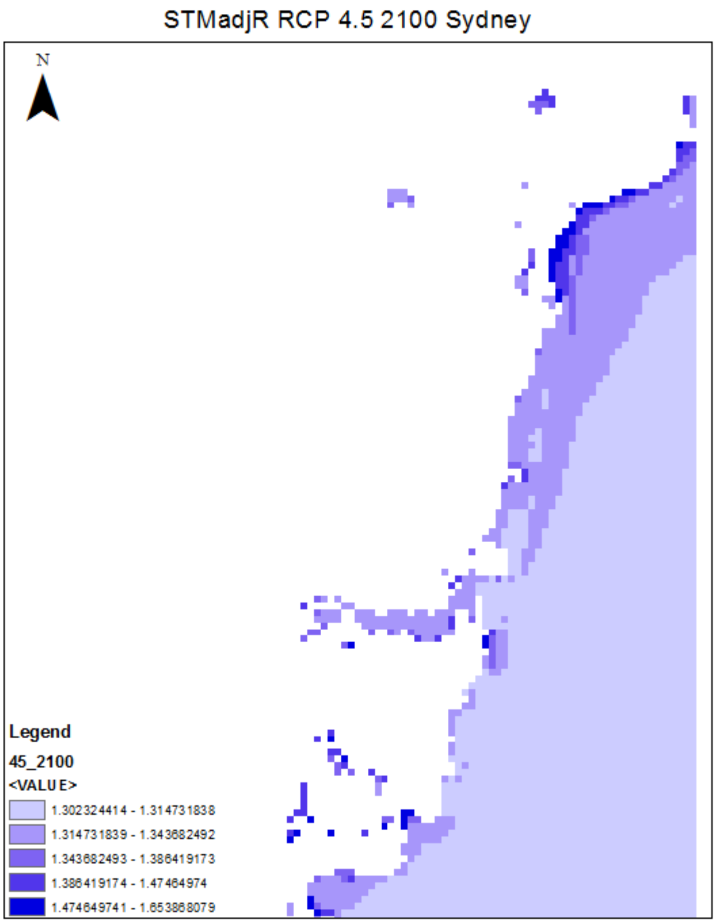


Figure 11: STMadjR RCP 4.5 Sydney

Figures 10 and 11 show the results of the STMadjR. A19 and A20 show the results for the two other scenarios. RCP 4.5 was chosen for presentation here because it is suitable to represent the relative moderate value change of the results.

The largest deviation of the statistical mean maxima values is Sydney in the RCP 8.5 scenario at the projection 2100.

The results for SMTR and STMadjR both exclude all values onshore. This comes from the integration of the GEBCO data, where each point with a positive water depth was excluded from the modeling.

4.2.3. STMT in comparison to STMR

The STMT comparison is intended to provide a test, if and when yes, how the calculated values exceed the identified rough thresholds for the exceedance of sea-level rise increase. This threshold was formulated at ±15% of the RSLR. STMT can provide information about if and how realistic the results are in comparison to empirical studies collected by Idier et al. (2019). On the other hand, these results do not provide information about how meaningful the exact quantification of the relation might be.

It is decided to choose the extreme RCP 8.5 scenario and the moderate scenario 4.5 for assessing the exceedance of STMT. The shortcoming of the given threshold of the review of Idier et al. (2019) is, that the studies used in this review all use different scenarios and partly uniform or non-uniform SLR. This lowers the reliability of this threshold additionally. Also, the deductive empirical and local to regional character of the studies cannot decline higher or lower-lying thresholds. Under this view, the STMT can be seen as orientation only.

To present the exceedance the positive exceedance only is considered, as no negative exceedance is possible with STMR and STMadjR. The reason for that lies in the mechanism of the tide constituent-dependent influence, which cannot be modeled with the data in use.

Deviation from the STMT is calculated by subtracting STMT from the STMR values. Figures 12 and 13 show the difference at both sites Houston and Sydney. Positive values show an exceedance of the +15% of RSLR at the site and negative values show areas under the threshold.

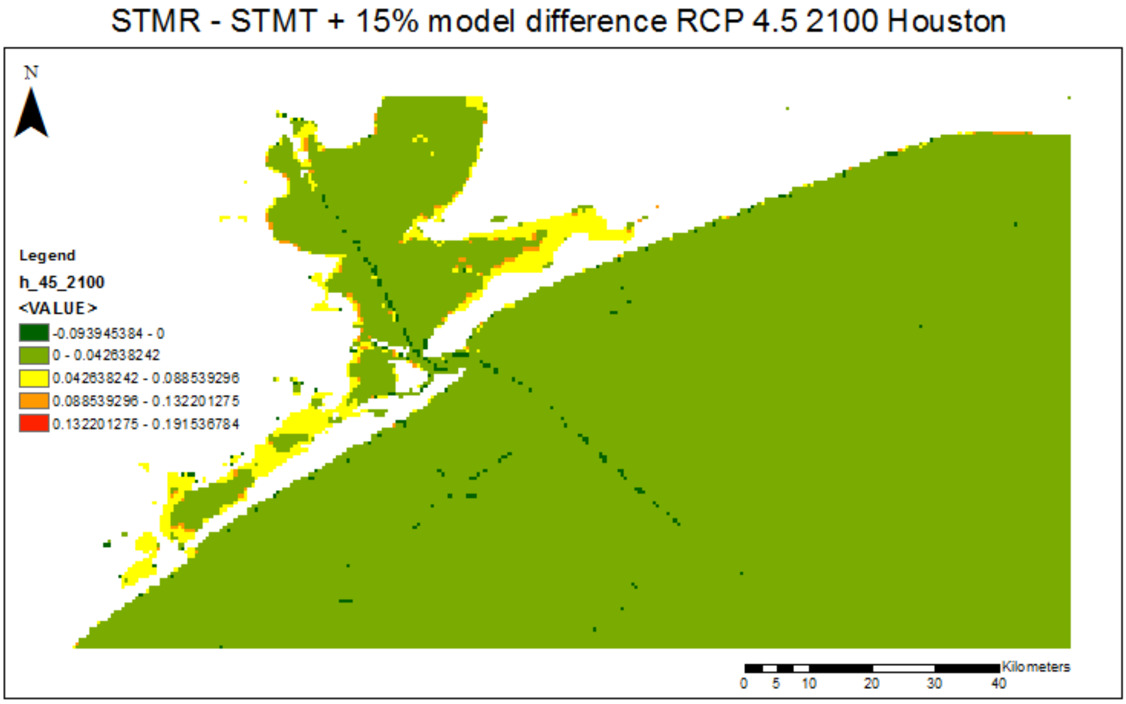


Figure 12: STMR minus STMT +15% RCP 4.5 2100 Houston map

Figure 12 has a slightly different color classification for presentation purposes in this case than figure 13. In RCP 4.5 at 2100 Figure 12 shows with yellow, orange, and red the positive deviation of STMR from the additive model plus 15%.

The definition of the threshold through the additive relation makes it additionally very complex to compare with.

Nonetheless, there is also more information to access through this circumstance. It can be seen, that the additive relation plus 15% is widely higher than the STMR model at Houston, which is the model with the naturally highest values without the negative feedback from adjNTR.

Similar observations can be made at the Sydney site. The site has overall more values clearly under the threshold in the same scenario as Houston. In the northern part of the site, where also the highest RSLR values occurred, also the highest exceedance can be observed.

The threshold exceeding values increase in number at the RCP 8.5 2100 cases, which can be found in A21.

Overall with STMT can be seen, that the values are not necessarily totally out of range with the applied non-adjusted or even calibrated and applied relations for SLR-tide interaction.

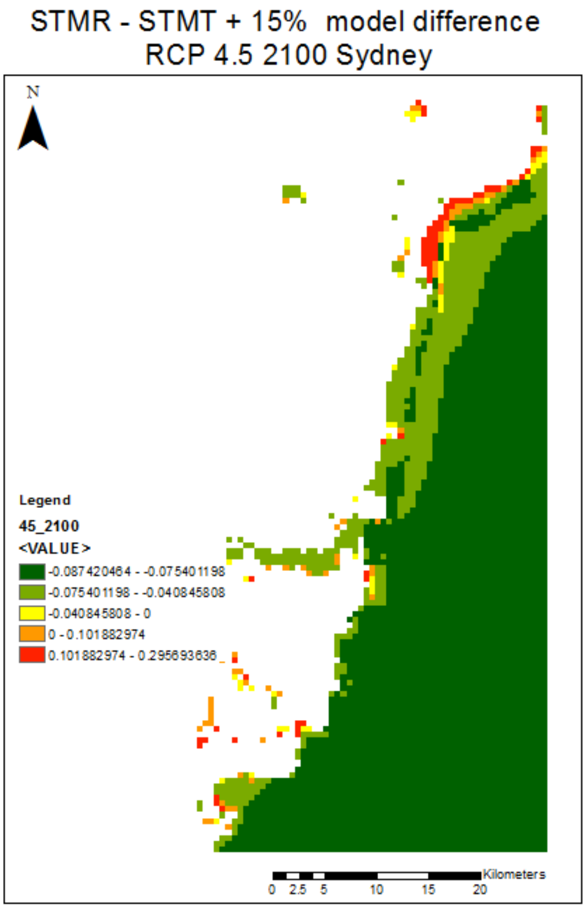


Figure 13: STMR minus STMT +15% RCP 4.5 2100 Sydney map

5. Discussion

The following discussion is divided into different parts to address the different layers of problems and questions sharply from each other. In the first part, the results were interpreted and the final core results are worked out. In the second part, these results are connected with the underlying data, the model setup, and other uncertainties, which might affect the interpretation of the results. In the last part of the discussion, the problem of benchmarking, comparability, and the possible field of application of such models in this field of research is addressed.

5.1. Result interpretation

For the result interpretation, the models are compared, regarding their general results and their spatial results. To interpret the results spatially, further discussion is needed about the empirical evidence of the model results.

STMR has the highest values as expected as there are no negative feedback loops included. STMadjR has slightly lower values as there is a negative feedback loop included for the non-tidal residuals. The effect of the negative feedback loop is not that high, because of the overall relatively low percentage of the non-tidal residuals on the total water height. The characteristics of this chosen parameter will be further discussed in 5.2.

Both simply mathematical described relations which add water depth and relative changes in water level based on the assumptions described in the methodology are identified as the main drivers for the assumed non-additive changes in sea-level induced and caused by RSLR. Referencing on the methodology and the cited studies, it is from high confidence, that there are and will be non-additive changes induced by sea-level rise through its influences on tides and meteorologically forced events as non-tidal residuals or so-called storm surges as extreme events.

Due to the fact, that especially the STM, STMR, and STMadjR values are exceeding the STMT threshold control value, it breaks down the main problem of the empirically low confidence of the exact numerical character and quantification of the possibly existing relation between the sea level rise and the tides and non-tidal residuals.

Idier et al. (2019) point out, that there are different results and that there is no uniform or generally derivable relation between the studies. It is more like an observation trend with numerous exceptions and different orders of magnitude.

Because of that, the result interpretation is focused on another part: the spatial character of the expected non-additive changes based on the derived relations. Even if the results are not suitable for delivering exactly quantified results regarding the expected changes, it can be shown, where non-additive changes can be expected in the future. This expectation can be seen in the difference between the two investigation sites and is described in the following section.

Sydney has higher tidal amplification than Houston (A2 and (Vousdoukas et al., 2018). Despite the difference in the parameter non-tidal residuals, Sydney is less likely hit by severe storm events (winter storms). NTR weight is not that much in the applied model, because of the relatively low values in comparison to tide and SLR. In comparison, Houston has a shallower shelf than Syndey and also lower tidal amplification (A1 & A2). Therefore Houston is hit more likely by severe tropical storm events with higher storm surges (Needham & Keim, 2012). This fact can be seen through the fact, that the 90,5 years return period non-tidal residuals nearly doubling on the Houston stations the values of the Sydney stations, which is a result of the higher peak values and more severe meteorological forcing more often. This can be read out in the reconstructed NTR data series by Tadesse & Wahl (2021).

These two diametral conditions of both sites lead under the applied models to very different consequences based on the results.

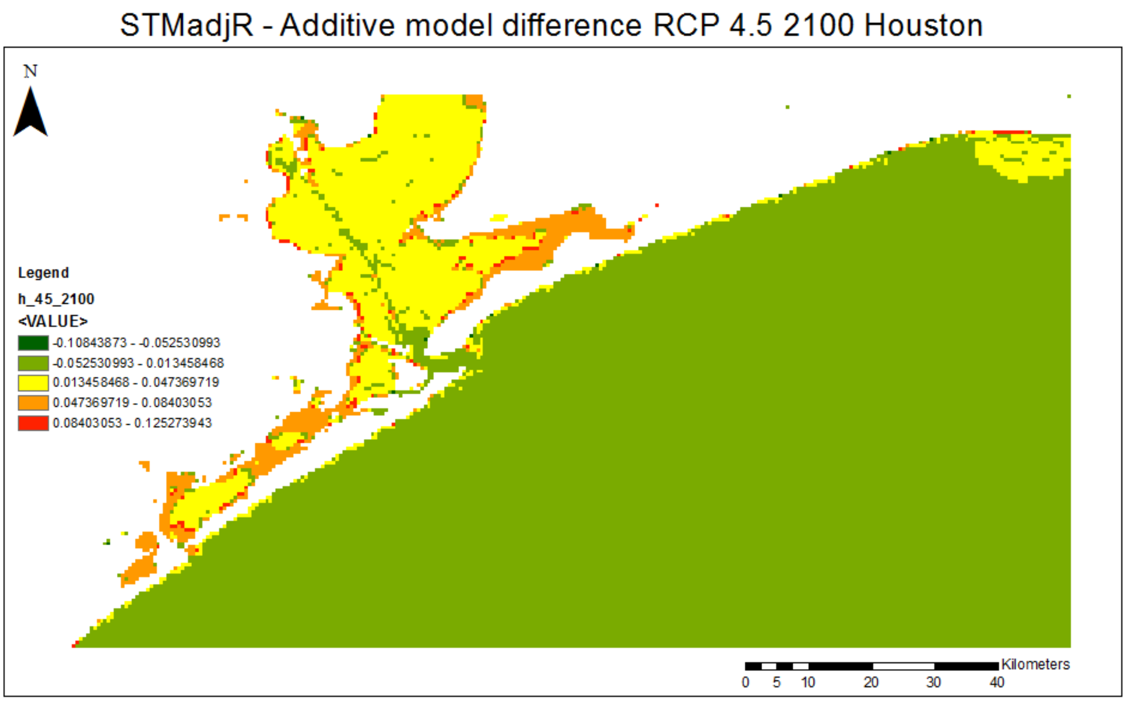


Figure 14: STMR - Additive model difference RCP 4.5 Houston Map

Positive and negative deviation from the additive-model results can be seen in figure 14. The map is the resulting form subtracting the additive model result from the STMadjR result concerning the same scenario and projection.

It can be seen, that there is a spatially large negative deviation in the offshore area. The Houston bight has a positive deviation, which means, that the STMadjR under the applied relation expects an increasing effect of the SLR on tides. Houston bay has quite shallow waters (A1), which is likely to intensify the effect of relative tidal increase because of a relatively high increase of the water depth by the RSLR there, even when the tidal amplification is overall not that large (especially not that large as in Sydney). Negative deviation leads back to the relative increase of the water depth as well.

An observation for both models is, that through the absolute values of the used parameters and the direct relativity through the applied relation, the effect of the relationship appears most in shallow water areas.

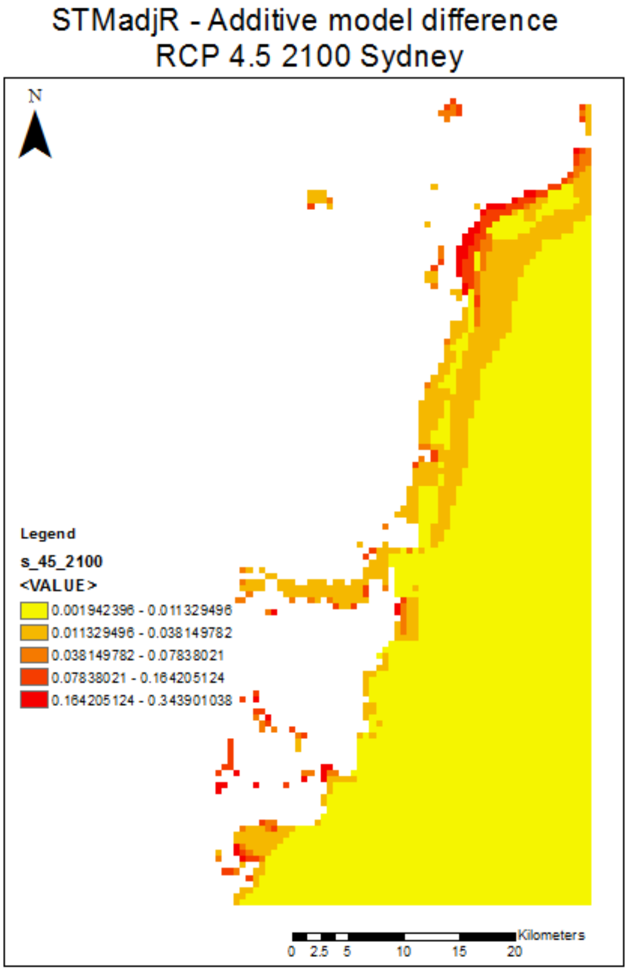


Figure 15: STMR - Additive model difference RCP 4.5 Sydney Map

At the Sydney site in figure 15, the values only deviate positively to the additive model, which means that the STMadjR exceeds the AM all over the investigation site. Most of the large changes are in the other part and all of them are in the shallower regions of the site.

No negative deviation of the values in comparison to the additive model can be explained with the different set of values: higher tidal amplification, deeper waters, and lower (absolute in comparison to Houston and relative to the other parameters at the Sydney site) NTR values.

This observation leads to the final result, that the derived and identified possibly occurring non-additive/non-linear relations between SLR, tide, and NTR are appearing differently at the sites in respect to their physical (water depths) and hydrological character.
Following the observation, the Houston site could expect overall lower average water heights caused by not changed meteorological conditions with the moderate increasing influence of its tidal amplification in the most shallow waters. At the Sydney site, it is vice versa, as there can be expected an increase of the tidal amplification with a very low decrease of the average NTR, which overall leads to a significant increase over the site.

These results of spatial very heterogenous non-additive effects even in this investigation sites from a local to regional scale shows, that additive models must be declined definitely for calculation of the influence of future sea-level rise changes on total water heights under different circumstances.

5.2. Model uncertainties

5.2.1. Variables and data

As stated in the methodological chapter the model and calculation are based on a set of assumptions, which led to the reduction for setting up the model by choosing variables and their statistical and spatial character. The choice for variables and their definition and calculation is discussed briefly in the following section. Specifically, this section focuses on the (non-spatial) statistical calculation of the variables, while 5.2.2. focuses on the spatial operations of the modeling process.
The basic idea of the chosen set of variables is taken by various studies like Hakkou et al. (2019), which also try to assess the variable total water height with tides, SLR, and a variable that represents the meteorological forcing of the sea surface and resulting in higher water levels. SLR is taken as spatially non-uniform RSLR relative to a temporal reference, which is in this case the year 2007. This SLR is then used to figure out the possible influence on the tides and the meteorological forcing of the sea surface. For the tide, it was decided to use the

highest astronomical tide. This decision includes the assumption, that the gravitational potentially occurring tide is the baseline for the highest total water levels. Contrary to this decision, NOAA for example uses more Mean Higher High Water (MHHW) as the baseline for total water heights calculations. It was decided not to use MHHW because the dataset with global coverage and MHHW as reference is unlikely to find. Besides the vertical reference, also a temporal reference is not in use specifically like a national datum epoche (NTDE) of NOAA. The reason for that is also the lack of suitable data assigned to the NTDE of NOAA. This can become an issue when it comes to the question, how the calculated data could be compared to a digital elevation model for inundation assessment.

Regarding the variables used for defining total water levels, the NTR variable is the most discussable variable next to the question of the interaction and the underlying probabilities of the coincidence. NTR is chosen because of the data provided by Tadesse & Wahl (2021). Mostly discussable at this point is the averaging of the daily values to yearly mean values of the NTR time series. This results in a strong elimination of the existing extreme values especially in Houston induced by severe tropical storms. So it must be considered, that under the prerequisite of the calculation of the return period out of yearly averaged daily maxima, not only the internal risk of the historically interpolated values plays a role, but also the fact, that these values are unlikely to represent the real extremes occurring in that areas. Averaged NTR values in use with their assigned return period of 90.5 years represent so an average and not extreme condition value. It should not be confused with the much higher storm surges occurring especially near Houston Bay.

This combination and character of variables are very important to document transparently and to be clear regarding the exact meaning of the calculated value. Even if the values would represent more extreme conditions, the purpose of the model is unlikely to address even storm surges, as there are more and additional physical effects, which have to be considered, when it comes to including storm surges.

Next to the question of the variables in use, it is the question of how high the evidence might be, that the probability can be assessed for the coincidence of the variables and their defined status: the sea level rise, a highest astronomical tide and a 90.5 years return period NTR. The coinciding of these variables could be possible but should not be unquestioned. Theories also vary dependent on the occurrence of these variables.

Idier et al. (2019) for example backing the theory of higher surges in lower water depth partly by referring to the shallow water equations but also adding, that wind stress as part of meteorological forcing produces higher surges at lower tides than at high tides. The complexity also rises, when the assumption is questioned, that high tide (e.g., HAT) and the highest non-tidal residuals are more likely to coincide. Horsburgh & Wilson (2007) expressed assumptions that the highest residuals are more likely to occur in rising tides and not necessarily at the peak of the tide.

Marsooli & Lin (2018) also show that there is quite some disparity regarding the tide and surge interaction, which partly includes, that the surges are not occurring at high tide.

There are also hints, that wave patterns can change the entire set of variables in different sea-level rise scenarios. (Fraile-Jurado et al., 2020)

It can be concluded, that the overall collection of studies provides a very opposing picture for interpretation and approximative generalization for total water level calculation.

Despite the uncertainties regarding the set of variables, the data can provide information about possible occurring non-linearities between the variables.

An additional challenge for assessing the probability of considering parameters is also the temporal variability of used parameters, especially the tide.

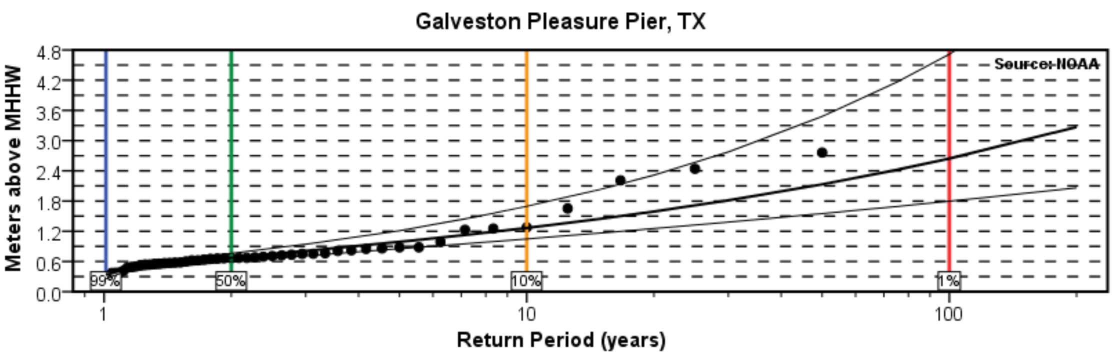


Figure 16: Galveston Pleasure Pear, TX RP meters above MHHW (https://tidesandcurrents.noaa.gov/est/curves.shtml?stnid=8771510)

NOAA shows with the chart in Figure 16 the complexity of the extreme water height assessment connecting the severity represented by height above MHHW with the entrance probability formulated with return periods. Connected with Figure 17 this shows, that there is not only spatial but also large temporal (intra-annual) variability and disparity.

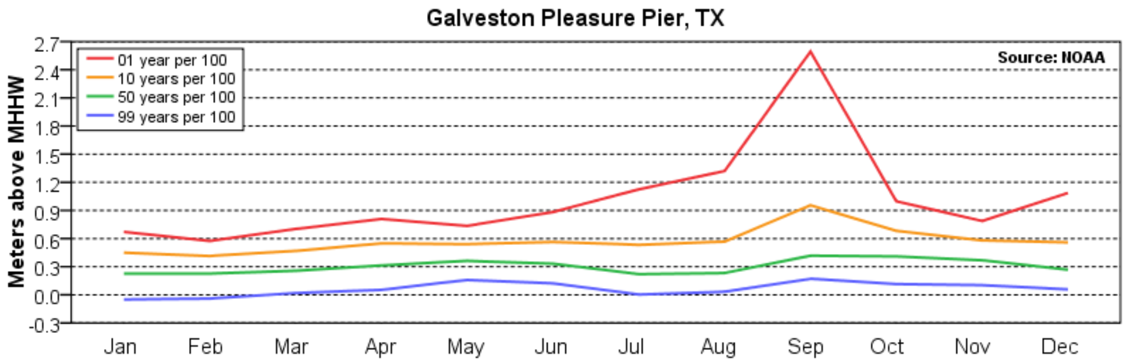


Figure 17: intra-annual RP distribution for meters above MHHW https://tidesandcurrents.noaa.gov/est/seasonal.shtml?stnid=8771510

Approximated probabilities for the occurrence of extreme level events must be seen under the prerequisite, that the probability is not distributed equally through a year as Figure 17 underlines for the tide gauge point in Galveston (Texas). Besides the intra-annual variability of entrance probabilities also inter-annual and even interdecadal oscillation of base parameters makes it even harder to create a precise approximation for an entrance probability for a coincidence.

The calculation of total water levels is facing problems of numerical transparency in this case, which can be improved only by a better understanding of the coinciding of the parameters and more precise and long-term available data with regional or global coverage.

Another option is to assign the extreme water level entrance probabilities into different scenario classes for underlying assumptions, temporal resolution and the choice of the parameter used exactly.

5.2.2. Spatial modeling

The spatial modeling part includes some uncertainties and is divided from the other discussion to set this topic apart. Spatial modeling and detailed discussion of the technical workflow is unlikely to be discussed in a scientific investigation.

Nevertheless, spatial modeling can be an important source of distortion of final values and also the appearance of the data.

Data from all three variables were interpolated for the modeling purpose. This inverse distance interpolation favors an interpolation of values the stronger the nearer the reference values are to them. Due to very limited reference points (e.g., HAT in Sydney), this technique seems to be very rough, but the only useful technique to manage the point data and for creating continuous raster datasets.

SLR data was mainly interpolated as well because the data was not granular enough to reach the exact coastline as the other data. Interpolation of SLR data also included, as with the other datasets, interpolation of data in locations, where the landmass exists. These data were mainly used for the modeling of the additive model relation. For the other data, the bathymetry data was used for the calculation additionally. Bathymetry data were recalculated, and every location with positive water depth values (equivalent to landmass) was set to no data. With this technique, it was possible to exclude every location onshore defined by the bathymetry data.

Other points regarding the interpolation and data are the missing locations in the Bay area near Houston (e.g., A19) and the non-connected raster values onshore (A16-17, A19-21).

The missing raster cells in the bay area can be explained with the interpolation of the NTR at the Houston site. In this case, the interpolation extent is limited because of the location of the stations. To avoid any distortion or further uncertainties it was decided to accept this missing data. In future calculations with more stations, the data could be interpolated as a global dataset with high station density at the coastlines. Data in between the coastlines could be also interpolated like the sea level rise data to fill data gaps near or at the coast. This workaround could lead to continuous data but adding also more uncertainty especially if there are bay areas without any data for calibration.

The non-connected raster values are a result of the interpolation explained before and the calculation with the inverted bathymetry data. This leads to identified data onshore in regions, where water depth was identified by the bathymetry dataset. A possible data cleansing process was not performed for providing the original data and to show this side effect of the simple map algebra operations.

An advantage of this simple modeling is the transparency of the process towards complex simulations.

5.2.3. Eulerian model type

In section 2.1. the differences between the basic model types were tried to explain and mainly two types were differentiated from the spatial perspective: eulerian and lagrangian referencing on the paper of Bontempi & Faravelli (1998). It is important to identify and assign a modeling approach to one of these views on spatial processes and to work out the assumptions and implications coming with the decision for one of these views.

The model and approach for calculating TWL in this thesis are assigned to eulerian model types. For calculating these water levels hydrological characteristics in form of water heights relative to temporal and vertical reference levels were discretized and recalculated with each other.

This leads compulsorily to the consequence, that the hydrological main character of a water body, interactions like currents, swells, and physically long waves are not considered. Justifiably it can be questioned if the vertical relation of the variables for calculating TWL can be differentiated from the horizontal movement of the sea surface and processes in the water body.

Even when this question cannot be answered at this point, most of the studies in this field dispense on a discussion of this very important limitation of their modeling approach.

In the case at hand, it is assumed, that the vertical movement can be approximated without the horizontal interaction between the used finite spatial entities used to discretize the hydrological variables.

A reason backing this assumption is also the already considered lagrangian modeled processes by the input datasets in the case of the HAT, partly the RSRL and the NTR.

5.3. Calibration and comparability to other studies

For testing the results of the models and calculations in this thesis, the results have to be compared to other data and tried to be benchmarked. This is a serious issue especially when it comes to comparing future projections from different models to each other.

There are different dimensions, where the results can try to be compared. First, the baseline without any sea level should be proved to be realistic with the data at all. The question is here if the data of Tadesse & Wahl (2021) and Vousdoukas et al. (2018) leads to a realistic range of values at the sites when they are added. At the Houston site, only reliable data from NOAA could be found to assess how realistic the baseline values (the year 2007) might be. Baseline values at 2007 without sea-level rise influence are 0.37m over MSL for the exact station location of Galveston (Tadesse & Wahl, 2021) and 0.38m as average for the whole site result.

These values are compared to the period of 2002-2020 in figure 18. The NTR values with RP of 90.5 are assigned to the period 1836-2015 and the highest astronomical tide to 1980-2014. It seems to be in an acceptable range in the highest percentage of observed values when monthly averaged at the gauge station over MSL. Usage of the return period and the HAT favors the peaks of the timeline and leads to an acceptable baseline produced by the data in use at the Houston site.

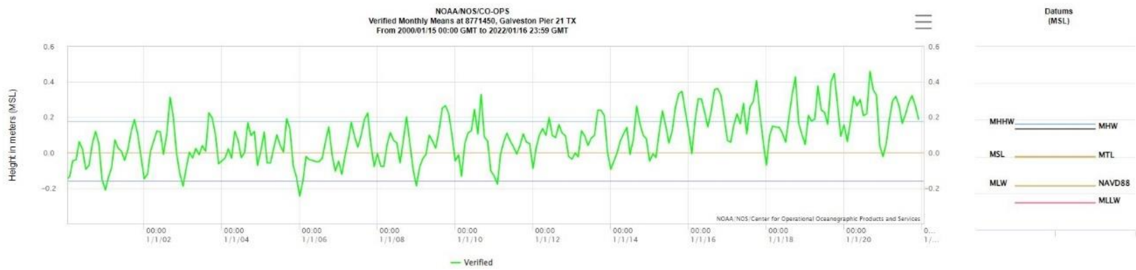


Figure 18: water height over MSL (NOAA) monthly averages Galveston Pier Texas 2002 – 2020 (https://tidesandcurrents.noaa.gov/waterlevels.html?id=8771450&units=metric&bdate=20000115&edate=20220116&timezone=GMT&datum=MSL&interval=m&action=)

No suitable and reliable data is available for Fort Denison or other stations around the Sydney site for testing the baseline parameter referencing to MSL vertically. Long term MSL trend from NOAA indicates high interannual amplifications of yearly averages, which even makes it more complex to verify.

Usage of different vertical and temporal datums makes this baseline calibration very complex.
Additionally, the validation gets more complex, when the future projections differ from each other, the vertical and temporal dates are different from region to region and the defined extremes are defined differently in each dataset.
A comparison to the global reanalysis dataset of surge and storm (Muis et al., 2016) shows the difference in the parameter definition.
At Galveston Pier station the difference at the base scenario without sea-level rise for an RP100 tide and surge height is approximately 0.67m. This remarkable difference can be explained with the different definitions of the surge and not the usage of non-tidal residuals.
For example, explained by McInnes et al. (2016) the definition of the wave set up and surge height can differ depending on the underlying data and calculation. Storm surges produce much higher water heights than the used NTR. This leads overall to a non-comparability between the datasets.
Even other datasets as SURGEDAT (http://surge.climate.lsu.edu/data.html) or GESLA (https://www.gesla.org/) provide no useful benchmarks, as they are not standardized mostly and the definition of the measured values is very intransparent.
This historically incomplete data situation will possibly favor the usage of reconstructed datasets as from Tadesse & Wahl (2021).

Another challenge and the mostly non-discussed problem of calibrating and benchmarking hydrological datasets is, that the datasets are mostly calibrated with root mean square error as metric and correlation analysis to benchmark datasets. This can lead to something, which could be partly described as an overfitting problem. That means, that the results might correlate in an acceptable range with the validation or benchmark data, but the underlying system does not rebuild the real-world conditions in an acceptable way, which could lead to misinterpretation and wrong values with changing parameters of the system in possible occurring future conditions.

6. Conclusion

Finally, the results and key takeaways are brought together and an outlook is provided on what further development could bring.

Indications from studies identified, that SLR will affect and mostly increase tides Arns et al. (2015). But there is only medium confidence about how generalizable these effects might be and how high the empirical evidence is there.

A negative feedback loop can decrease meteorological forced extremes like non-tidal residuals or storm surges.

Quantification of the strength of the influence of SLR on those parameters is not possible as there is only low confidence about the exact character. Additionally, the effects might be not uniform and there are already exceptions documented. (Idier et al., 2019)

All these facts make the setup of a parametric model for modeling the possible non-linear effect between SLR, tide, and NTR very complex. Nevertheless, it was possible to show possible differences if simple influences are considered in two very different investigation sites in Sydney and Houston.

The final results of STMadjR showed that areas with higher tidal amplification are more hit by the direct influence of SLR (Sydney), while at sites with meteorological forcing this could mean, that there could be a slight decrease for the meteorological forced extremes (Houston) under the assumption of no increase of the meteorological forcing.

The assumption reveals the conflict for modeling coastal hazard on a multi-regional or global scale because there might depend on the characteristics of the hydrological parameters and the shelf geometry, different main stresses, which drive future extreme events.

Parametric model approaches as applied in this study face problems with empirical evidence because of reducing the system complexity to their parameters and their imitation of the dynamic system. But for modeling basic hazards on bigger scales parametric models are still very powerful. This study has shown the beginning of a possible non-additive coastal hazard calculation under consideration of three active hydrological parameters. Even when there is only medium confidence overall, the model can show clearly that there is no way for a simple additive calculation as it would lead to massive misclassification of future hazards and would undermine the complex spatial disparity of hazard development. It also helps to understand simplified hydrological mechanisms and the results of their application under changing sea levels in the future. Commonly used hazard metrics like the RSLR on a specific location for estimation of how extreme water levels might endanger coastal structures and communities can be seen as not meaningful enough if used isolated and should not be used because they do not provide any information related to a vertical and temporal scale. Vertically it is extremely important to understand how the RSLR will interact with other parameters and temporally it is indispensable to define what happens when what coincides.

In the parametric set of the model of this study, long-term averaged meteorological conditions were used as non-tidal residuals and assumed to coincide with HAT and the RSLR. In the future, it is important to define clearly which coincidence is modeled and what is assumed as a result because only then resilience can be built up properly. Results can vary largely depending on the used set of parameters and their statistical character, which has to be documented transparently and discussed. A direct consequence of further intransparent models could be the wrong synthesis about the character and the severity of future extreme sea levels. Therefore it should be possible to differentiate if the average conditions are increasing the water levels (chronic) or if extraordinary peaks at severe events (acute) can be expected.

Chapter 5.3 also shows one of the main problems of interpolations of conditions in the future, because of the nearly impossible comparability of studies and the lack of calibration material. Comparability is very difficult because of the different definitions and sets of parameters and the calibration is questionable under the assumption of not yet measured non-linear changes between the parameters. Even when studies compare similar to each other, it can be random and the underlying assumption might lead to extreme misjudgment for future conditions, which could be assumed for the additive models in particular.

The next steps for model improvements in the further collection of empirical evidence and testing of the influence of RSLR on other hydrological parameters (like storm surges). Even passive effects and consequences like erosion of the shoreline and subsidence through massive groundwater extraction should be considered. Modeling of possible inundation extents onshore will also need to discuss the comparability of global vertical and temporal references like the datum and how it can be projected on a digital elevation model.

References

Arias, P. A., N. Bellouin, E. Coppola, R. G. Jones, G. Krinner, J. Marotzke, V. Naik, M. D. Palmer, G-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P. W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R. P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J. G. Canadell, C. Cassou, A. Cherchi, W. Collins, W. D. Collins, S. L. Connors, S. Corti, F. Cruz, F. J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F. J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J. S. Fuglestvedt, J. C. Fyfe, N. P. Gillett, L. Goldfarb, I. Gorodetskaya, J. M. Gutierrez, R. Hamdi, E. Hawkins, H. T. Hewitt, P. Hope, A. S. Islam, C. Jones, D. S. Kaufman, R. E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J-Y. Lee, J. Li, T. Mauritsen, T. K. Maycock, M. Meinshausen, S-K. Min, P. M. S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A. C. Ruane, L. Ruiz, J-B. Sallée, B. H. Samset, S. Sathyendranath, S. I. Seneviratne, A. A. Sörensson, S. Szopa, I. Takayabu, A-M. Treguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, K. Zickfeld. (2021). Technical summary. In: Climate change 2021: The physical science basis. In Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (Ed.), *Sixth assessment report of the intergovernmental panel on climate change.* Cambridge University Press. In Press.

Arns, A., Wahl, T [T.], Dangendorf, S., & Jensen, J. (2015). The impact of sea level rise on storm surge water levels in the northern part of the german bight. *Coastal Engineering*, *96*, 118–131. https://doi.org/10.1016/j.coastaleng.2014.12.002&domain=pdf

Benveniste, J., Cazenave, A., Vignudelli, S., Fenoglio-Marc, L., Shah, R., Almar, R., Andersen, O., Birol, F., Bonnefond, P., Bouffard, J., Calafat, F., Cardellach, E., Cipollini, P., Le Cozannet, G., Dufau, C., Fernandes, M. J., Frappart, F., Garrison, J., Gommenginger, C., . . . Wöppelmann, G. (2019). Requirements for a coastal hazards observing system. *Frontiers in Marine Science*, *6*, Article 348. https://doi.org/10.3389/fmars.2019.00348

Bilskie, M. V., Hagen, S. C [S. C.], Alizad, K [K.], Medeiros, S. C [S. C.], Passeri, D. L [D. L.], Needham, H. F [H. F.], & Cox, A. (2016). Dynamic simulation and numerical analysis of hurricane storm surge under sea level rise with geomorphologic changes along the northern gulf of mexico. *Earth's Future*, *4*(5), 177–193. https://doi.org/10.1002/2015EF000347

Bontempi, F. & Faravelli, L. (1998). Langrangian/eulerian description of dynamic systems. *Journal of Engineering Mechanics*.

Chen, C., Lin, Z., Beardsley, R. C., Shyka, T., Zhang, Y., Xu, Q., Qi, J., Lin, H., & Xu, D. (2021). Impacts of sea level rise on future storm-induced coastal inundations over massachusetts coast. *Natural Hazards*, *106*(1), 375–399. https://doi.org/10.1007/s11069-020-04467-x

Dall'Osso, F., Dominey-Howes, D., Moore, C., Summerhayes, S., & Withycombe, G. (2014). The exposure of sydney (australia) to earthquake-generated tsunamis, storms and sea level rise: A probabilistic multi-hazard approach. *Scientific Reports*, *4*, 7401. https://doi.org/10.1038/srep07401

Dettmering, D., Müller, F. L., Oelsmann, J., Passaro, M., Schwatke, C., Restano, M., Benveniste, J., & Seitz, F. (2021). *NorthSEAL: A new Dataset of Sea Level Changes in the North Sea from Satellite Altimetry.* https://doi.org/10.5194/essd-2021-103

Dodet, G., Bertin, X., Bouchette, F., Gravelle, M., Testut, L., & Wöppelmann, G. (2019). Characterization of sea-level variations along the metropolitan coasts of France: Waves, tides, storm surges and long-term changes. *Journal of Coastal Research*, *88*(sp1), 10. https://doi.org/10.2112/SI88-003.1

Doxani, G., Papadopoulou, M., Lafazani, P., Pikridas, C., & Tsakiri-Strati, M. (2012). Shallow-watter bathymetry over variable bottom types using multispectral worldview-2 image. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XXXIX-B8*, 159–164. https://doi.org/10.5194/isprsarchives-XXXIX-B8-159-2012

Farrell, W. E., & Clark, J. A. (1976). On postglacial sea level. *Geophysical Journal of the Royal Astronomical Society*, *46*(3), 647–667. https://doi.org/10.1111/j.1365-246X.1976.tb01252.x

Fraile-Jurado, P., Guisado-Pintado, E., Álvarez-Francoso, J. I., Díaz-Cuevas, P., & Ojeda-Zújar, J. (2020). Wave energy patterns under different sea level rise (slr) probabilities in the andalusian atlantic coast. *Journal of Coastal Research*, *95*(sp1), 1088. https://doi.org/10.2112/SI95-212.1

Garner, A. J., Mann, M. E., Emanuel, K. A., Kopp, R. E., Lin, N., Alley, R. B., Horton, B. P., DeConto, R. M., Donnelly, J. P., & Pollard, D. (2017). Impact of climate change on new york city's coastal flood hazard: Increasing flood heights from the preindustrial to 2300 ce. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(45), 11861–11866. https://doi.org/10.1073/pnas.1703568114

H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.) (Ed.). (2019). *IPCC Special Report Ocean and Cryosphere in a Changing Climate (SROCC)*. In Press.

Hague, B. S., & Taylor, A. J. (2021). Tide-only inundation: A metric to quantify the contribution of tides to coastal inundation under sea-level rise. *Natural Hazards*, *107*(1), 675–695. https://doi.org/10.1007/s11069-021-04600-4

Haigh, I. D. (2017). Tides and water levels. In J. Carlton, P. Jukes, & Y. S. Choo (Eds.), *Encyclopedia of maritime and offshore engineering* (pp. 1–13). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118476406.emoe122

Haigh, I. D., MacPherson, L. R., Mason, M. S., Wijeratne, E. M. S., Pattiaratchi, C. B., Crompton, R. P., & George, S. (2014). Estimating present day extreme water level exceedance probabilities around the coastline of australia: Tropical cyclone-induced storm surges. *Climate Dynamics*, *42*(1-2), 139–157. https://doi.org/10.1007/s00382-012-1653-0

Hakkou, M., Maanan, M., Belrhaba, T., Leone, F., Benmohammadi, A., El khalidi, K., & Zourarah, B. (2019). Assess and mapping the flooding hazards using geospatial tools and empirical model along kenitra coast, morocco. *Ocean & Coastal Management*, *169*, 264–272. https://doi.org/10.1016/j.ocecoaman.2018.12.032

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J [Robert James], Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C., & Levermann, A. (2014).

Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3292–3297. https://doi.org/10.1073/pnas.1222469111

Horsburgh, K. J., & Wilson, C. (2007). Tide-surge interaction and its role in the distribution of surge residuals in the north sea. *Journal of Geophysical Research*, *112*(C8). https://doi.org/10.1029/2006JC004033

Idier, D., Bertin, X., Thompson, P., & Pickering, M. D [Mark D.] (2019). Interactions between mean sea level, tide, surge, waves and flooding: Mechanisms and contributions to sea level variations at the coast. *Surveys in Geophysics*, *40*(6), 1603–1630. https://doi.org/10.1007/s10712-019-09549-5

Kerle, N., & Müller, A. (2013). Megacities and natural hazards. In P. T. Bobrowsky (Ed.), *Encyclopedia of Earth Sciences Series. Encyclopedia of Natural Hazards* (pp. 660–664). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_231

Lee, T.-C., Knutson, T. R., Nakaegawa, T., Ying, M., & Cha, E. J. (2020). Third assessment on impacts of climate change on tropical cyclones in the typhoon committee region – part I: Observed changes, detection and attribution. *Tropical Cyclone Research and Review*, *9*(1), 1–22. https://doi.org/10.1016/j.tcrr.2020.03.001

Lickley, M. J., Lin, N., & Jacoby, H. D. (2014). Analysis of coastal protection under rising flood risk. *Climate Risk Management*, *6*, 18–26. https://doi.org/10.1016/j.crm.2015.01.001

Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., & Picot, N. (2020). *FES2014 global ocean tides atlas: design and performances.* https://doi.org/10.5194/os-2020-96

Lyddon, C. E., Brown, J. M., Leonardi, N., Saulter, A., & Plater, A. J. (2019). Quantification of the uncertainty in coastal storm hazard predictions due to wave-current interaction and wind forcing. *Geophysical Research Letters*, *46*(24), 14576–14585. https://doi.org/10.1029/2019GL086123

Marsooli, R., & Lin, N. (2018). Numerical modeling of historical storm tides and waves and their interactions along the U.S. East and gulf coasts. *Journal of Geophysical Research: Oceans*, *123*(5), 3844–3874. https://doi.org/10.1029/2017JC013434

McInnes, K. L., Macadam, I., Hubbert, G., & O'Grady, J. (2013). An assessment of current and future vulnerability to coastal inundation due to sea-level extremes in victoria, southeast australia. *International Journal of Climatology*, *33*(1), 33–47. https://doi.org/10.1002/joc.3405

McInnes, K. L., White, C. J., Haigh, I. D., Hemer, M. A., Hoeke, R. K., Holbrook, N. J., Kiem, A. S., Oliver, E. C. J., Ranasinghe, R [Roshanka], Walsh, K. J. E., Westra, S., & Cox, R. (2016). Natural hazards in australia: Sea level and coastal extremes. *Climatic Change*, *139*(1), 69–83. https://doi.org/10.1007/s10584-016-1647-8

Muis, S., Verlaan, M [Martin], Winsemius, H. C., Aerts, J. C. J. H., & Ward, P. J. (2016). A global reanalysis of storm surges and extreme sea levels. *Nature Communications*, *7*, 11969. https://doi.org/10.1038/ncomms11969

Needham, H. F [Hal F.], & Keim, B. D. (2012). A storm surge database for the US gulf coast. *International Journal of Climatology*, *32*(14), 2108–2123. https://doi.org/10.1002/joc.2425

Neuwirth, C., Hofer, B., & Peck, A. (2015). Spatiotemporal processes and their implementation in spatial system dynamics models. *Journal of Spatial Science*, *60*(2), 277–288. https://doi.org/10.1080/14498596.2015.997316

Oppenheimer, M., B.C. Glavovic J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari. (2019). Sea level rise and implications for low-lying islands, coasts and communities supplementary material. In H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.) (Ed.), *Ipcc special report ocean and cryosphere in a changing climate (srocc).* In Press.

Passeri, D. L [Davina L.], Hagen, S. C [Scott C.], Plant, N. G., Bilskie, M. V., Medeiros, S. C [Stephen C.], & Alizad, K [Karim] (2016). Tidal hydrodynamics under future sea level rise and coastal morphology in the northern gulf of mexico. *Earth's Future*, *4*(5), 159–176. https://doi.org/10.1002/2015EF000332

Pickering, M. D [M. D.], Horsburgh, K. J., Blundell, J. R., Hirschi, J.-M., Nicholls, R. J [R. J.], Verlaan, M [M.], & Wells, N. C. (2017). The impact of future sea-level rise on the global tides. *Continental Shelf Research*, *142*, 50–68. https://doi.org/10.1016/j.csr.2017.02.004

R.K. Pachauri and L.A. Meyer (Ed.). (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

Rego, J. L., & Li, C. (2010). Nonlinear terms in storm surge predictions: Effect of tide and shelf geometry with case study from hurricane rita. *Journal of Geophysical Research*, *115*(C6). https://doi.org/10.1029/2009JC005285

Røed, L. P. (2019). *Atmospheres and Oceans on Computers*. Springer International Publishing. https://doi.org/10.1007/978-3-319-93864-6

Schlund, M., Lauer, A., Gentine, P., Sherwood, S. C., & Eyring, V. (2020). Emergent constraints on equilibrium climate sensitivity in cmip5: Do they hold for cmip6? *Earth System Dynamics*, *11*(4), 1233–1258. https://doi.org/10.5194/esd-11-1233-2020

Scyphers, S. B., Beck, M. W., Furman, K. L., Haner, J., Josephs, L. I., Lynskey, R., Keeler, A. G., Landry, C. E., Powers, S. P., Webb, B. M., & Grabowski, J. H. (2019). A waterfront view of coastal hazards: Contextualizing relationships among geographic exposure, shoreline type, and hazard concerns among coastal residents. *Sustainability*, *11*(23), 6687. https://doi.org/10.3390/su11236687

Stephens, S., Bell, R., & Lawrence, J. (2017). Applying principles of uncertainty within coastal hazard assessments to better support coastal adaptation. *Journal of Marine Science and Engineering*, *5*(3), 40. https://doi.org/10.3390/jmse5030040

Sweet, W. V., Genz, A. S., Obeysekera, J., & Marra, J. J. (2020). A regional frequency analysis of tide gauges to assess pacific coast flood risk. *Frontiers in Marine Science*, *7*, Article 581769. https://doi.org/10.3389/fmars.2020.581769

Tadesse, M. G., & Wahl, T [Thomas] (2021). A database of global storm surge reconstructions. *Scientific Data*, *8*(1), 125. https://doi.org/10.1038/s41597-021-00906-x

Toimil, A., Losada, I. J., Camus, P., & Díaz-Simal, P. (2017). Managing coastal erosion under climate change at the regional scale. *Coastal Engineering*, *128*, 106–122. https://doi.org/10.1016/j.coastaleng.2017.08.004

Torresan, S., Gallina, V., Gualdi, S., Bellafiore, D., Umgiesser, G., Carniel, S., Sclavo, M., Benetazzo, A., Giubilato, E., & Critto, A. (2019). Assessment of climate change impacts in the north adriatic coastal area. Part I: A multi-model chain for the definition of climate change hazard scenarios. *Water*, *11*(6), 1157. https://doi.org/10.3390/w11061157

van Westen, R. M., & Dijkstra, H. A. (2021). Ocean eddies strongly affect global mean sea-level projections. *Science Advances*, *7*(15). https://doi.org/10.1126/sciadv.abf1674

Vecchi, G., Landsea, C., Zhang, W., Villarini, G., & Knutson, T. (2021). *Changes in Atlantic Major Hurricane Frequency Since the Late-19th Century.* https://doi.org/10.21203/rs.3.rs-153527/v1

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M [Martin], Jevrejeva, S., Jackson, L. P., & Feyen, L. (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nature Communications*, *9*(1), 2360. https://doi.org/10.1038/s41467-018-04692-w

Wainwright, D. J., Ranasinghe, R [R.], Callaghan, D. P., Woodroffe, C. D., Cowell, P. J., & Rogers, K. (2014). An argument for probabilistic coastal hazard assessment: Retrospective examination of practice in new south wales, australia. *Ocean & Coastal Management*, *95*, 147–155. https://doi.org/10.1016/j.ocecoaman.2014.04.009

Walsh, K., White, C. J., McInnes, K., Holmes, J., Schuster, S., Richter, H., Evans, J. P., Di Luca, A., & Warren, R. A. (2016). Natural hazards in australia: Storms, wind and hail. *Climatic Change*, *139*(1), 55–67. https://doi.org/10.1007/s10584-016-1737-7

Wang, J., Kim, H.-M., & Chang, E. K. M. (2017). Changes in northern hemisphere winter storm tracks under the background of arctic amplification. *Journal of Climate*, *30*(10), 3705–3724. https://doi.org/10.1175/JCLI-D-16-0650.1

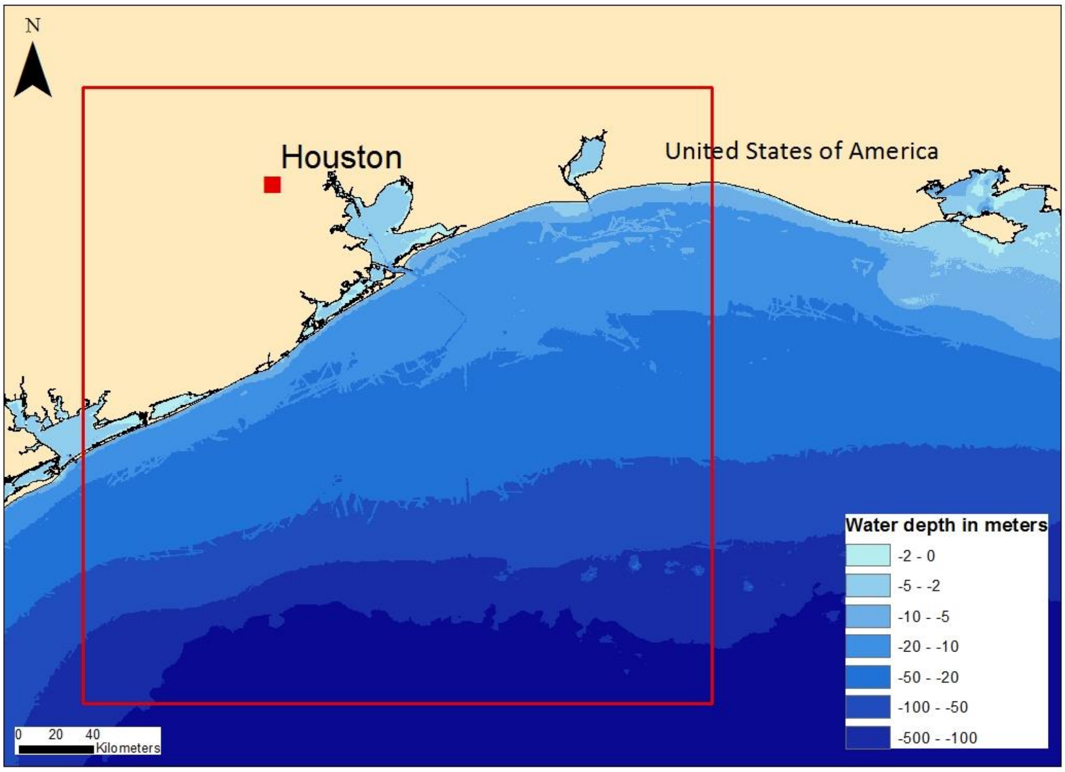
Weaver, R. J., & Slinn, D. N. (2010). Influence of bathymetric fluctuations on coastal storm surge. *Coastal Engineering*, *57*(1), 62–70. https://doi.org/10.1016/j.coastaleng.2009.09.012

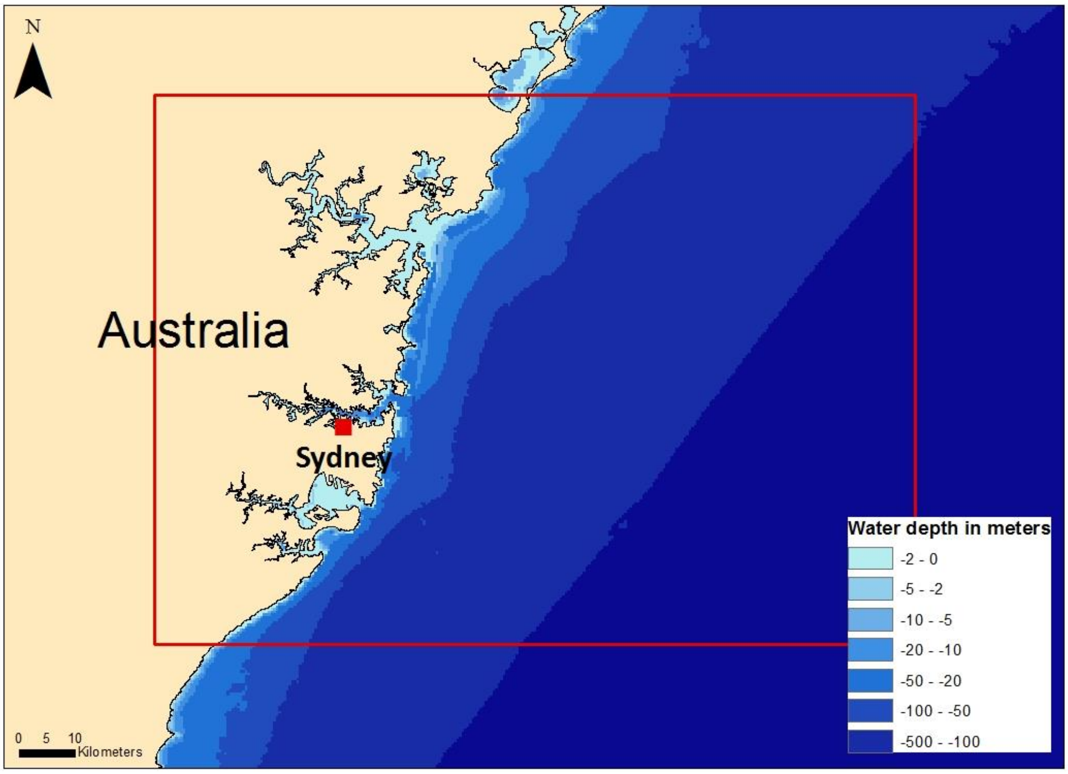
Woodworth, P. L., Melet, A., Marcos, M., Ray, R. D., Wöppelmann, G., Sasaki, Y. N., Cirano, M., Hibbert, A., Huthnance, J. M., Monserrat, S., & Merrifield, M. A. (2019). Forcing factors affecting sea level changes at the coast. *Surveys in Geophysics*, *40*(6), 1351–1397. https://doi.org/10.1007/s10712-019-09531-1

Zhang, G., Murakami, H., Knutson, T. R., Mizuta, R., & Yoshida, K. (2020). Tropical cyclone motion in a changing climate. *Science Advances*, *6*(17), eaaz7610. https://doi.org/10.1126/sciadv.aaz7610

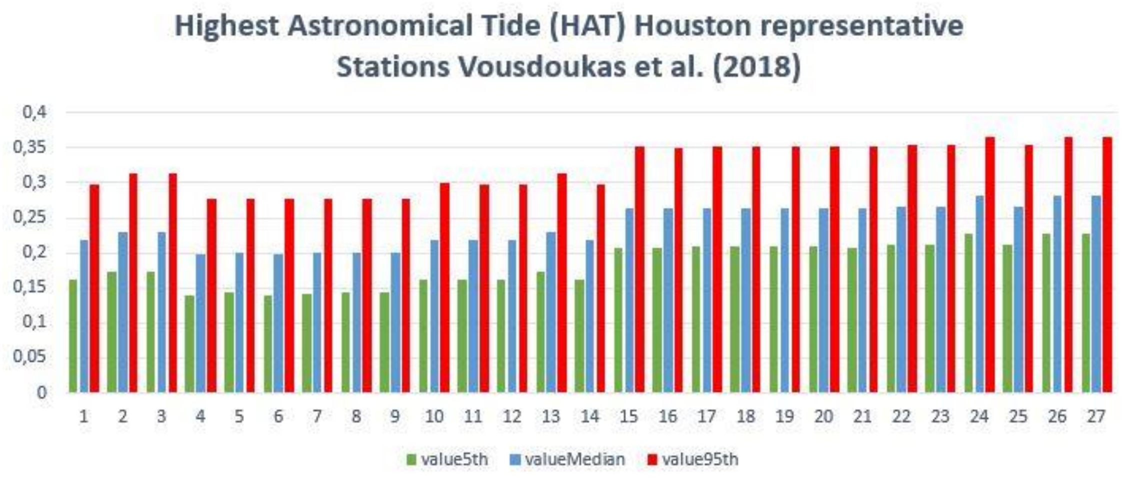
Appendix

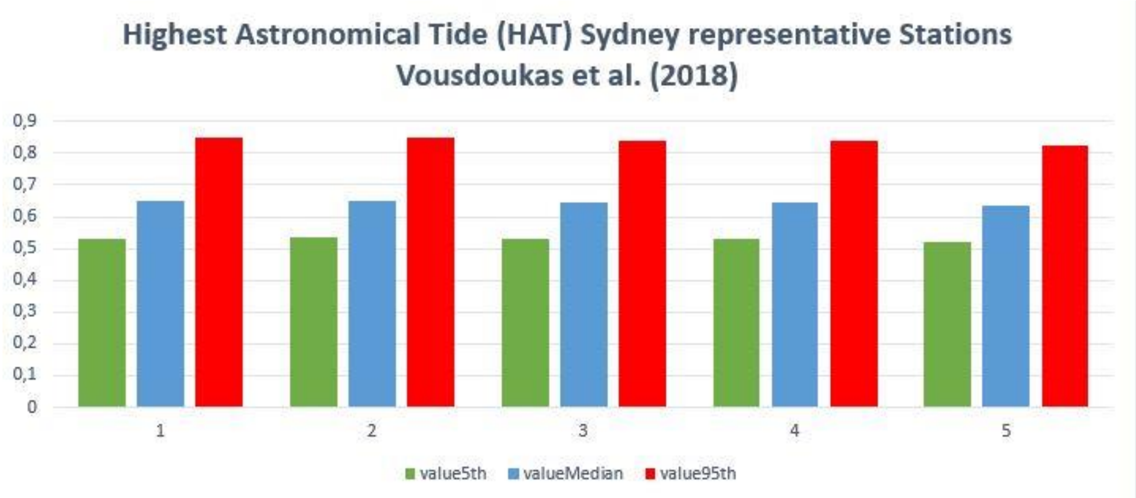
A1: Water depth maps Houston and Syndey



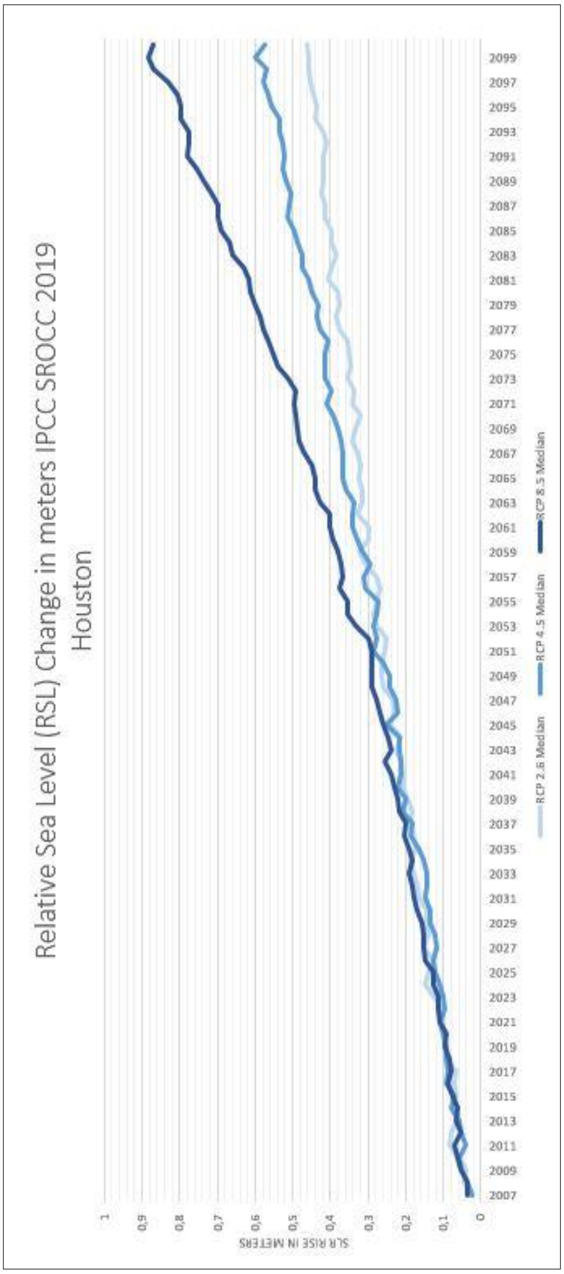


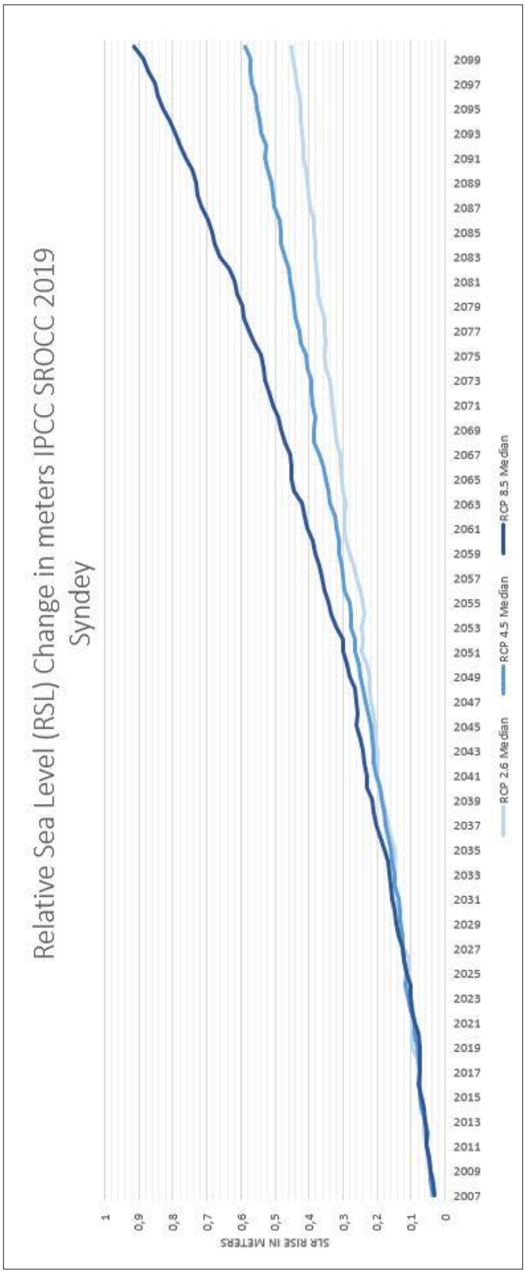
A2: HAT station values Vousdoukas et al (2018)





A3: Relative Sea Level Rise IPCC SROCC 2019 Houston and Sydney





A4: Non-tidal residuals (mean of yearly mean of daily maxima) Houston at the stations in the region in meters (Tadesse & Wahl, 2021)

Freeport

	Mean	Median
20cr	0,085580711	0,085885834
era20c	0,085582116	0,084610443
erafive	0,083962129	0,084156927
eraint	0,084029428	0,082939026
merra	0,083651331	0,083103985

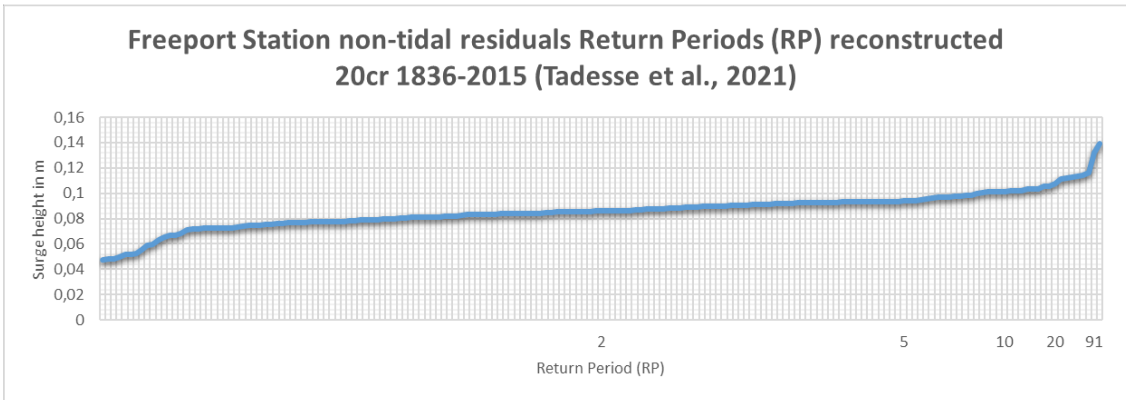
Galveston

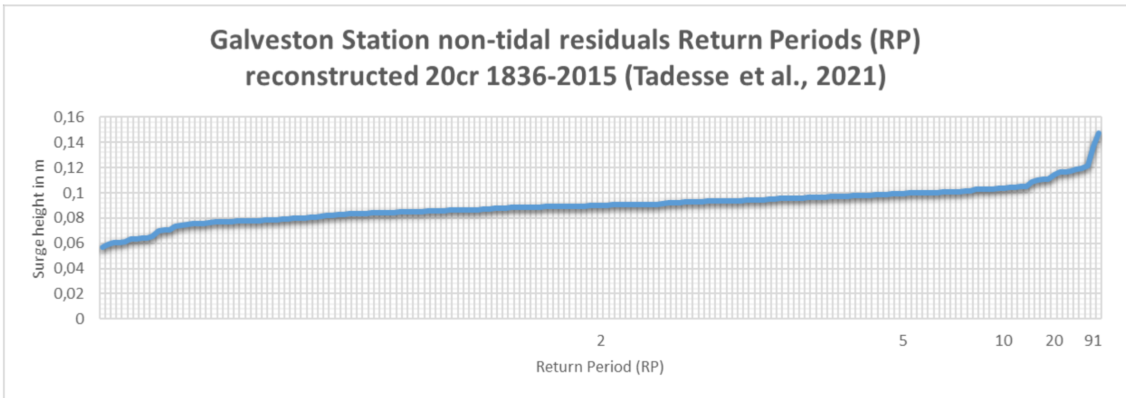
	Mean	Median
20cr	0,089966759	0,089936395
era20c	0,090043236	0,090405701
erafive	0,099509786	0,099063975
eraint	0,099568757	0,097962956
merra	0,099564473	0,098367446

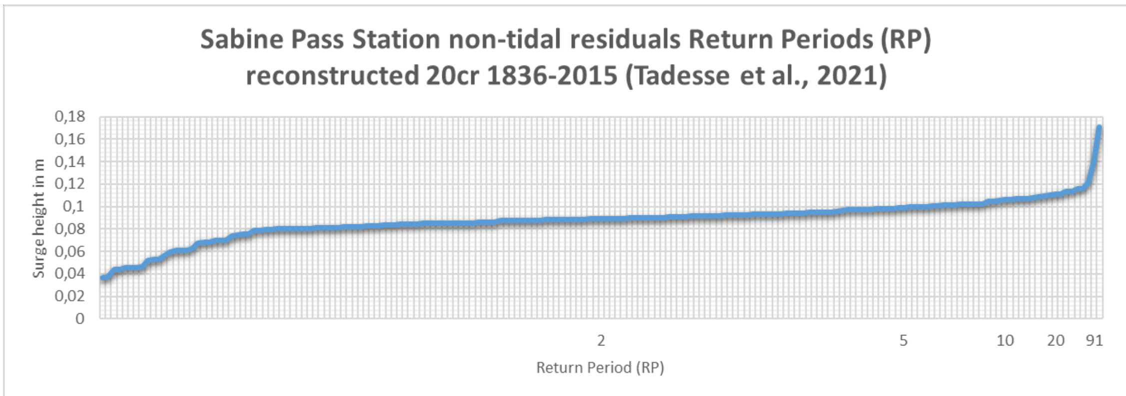
Sabine Pass

	Mean	Median
20cr	0,087647518	0,088911613
era20c	0,087495299	0,0880154
erafive	0,087649053	0,089294194
eraint	0,087616426	0,087274882
merra	0,087658638	0,087225625

A5: Return Periods NTR Houston







A6: Non-tidal residuals (mean of yearly mean of daily maxima) Sydney at the stations in the region in meters (Tadesse & Wahl, 2021)

Fort Denison

	Mean	Median
20cr	0,048982813	0,048889659
era20c	0,048981481	0,048552246
erafive	0,045454897	0,045079444
eraint	0,045384729	0,046821668
merra	0,045248756	0,043767207

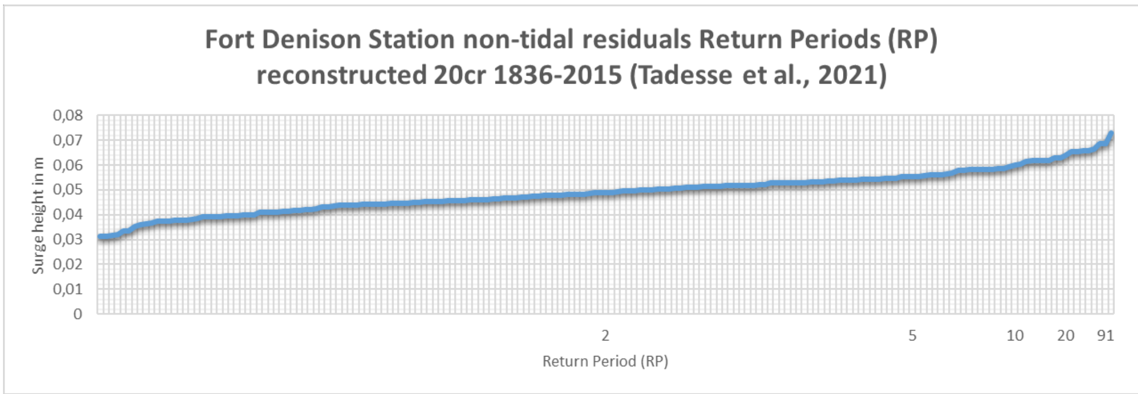
Newcastle

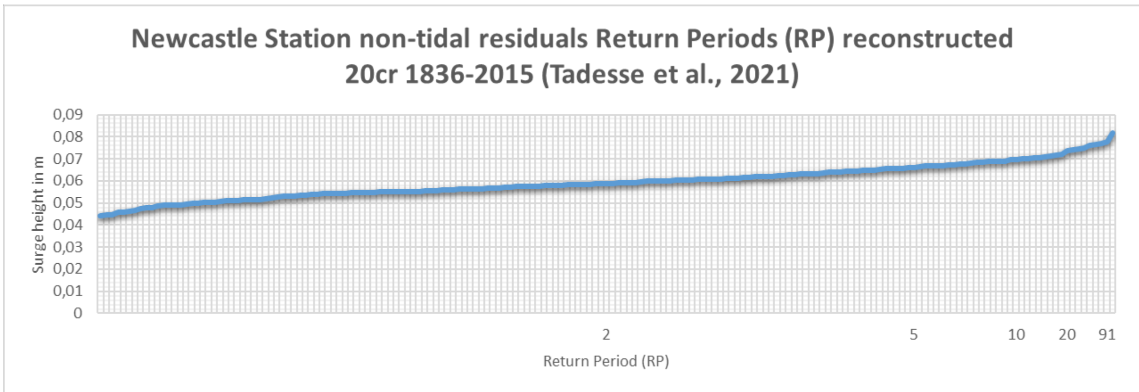
	Mean	Median
20cr	0,059440372	0,058757638
era20c	0,059439138	0,058930644
erafive	0,052412440	0,051744252
eraint	0,052353931	0,052539608
merra	0,052063273	0,051875652

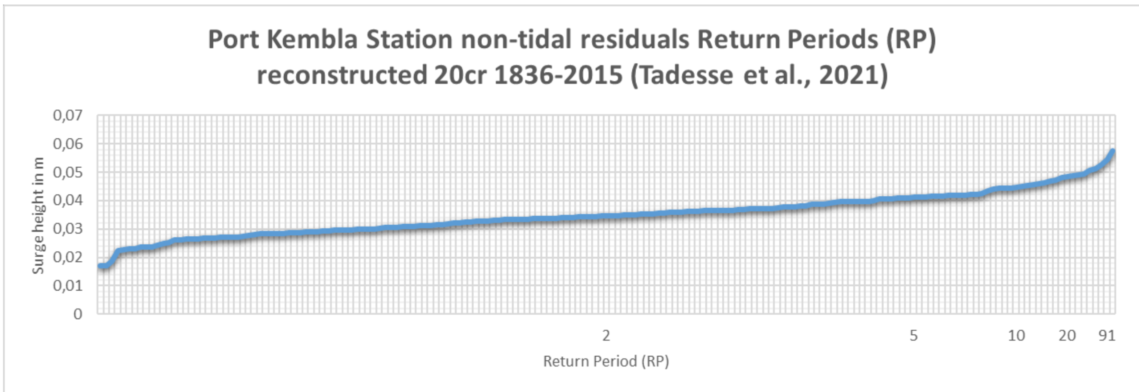
Port Kembla

	Mean	Median
20cr	0,034912804	0,034586847
era20c	0,034922373	0,034480898
erafive	0,034911237	0,034590557
eraint	0,034837605	0,035014695
merra	0,034899396	0,035100256

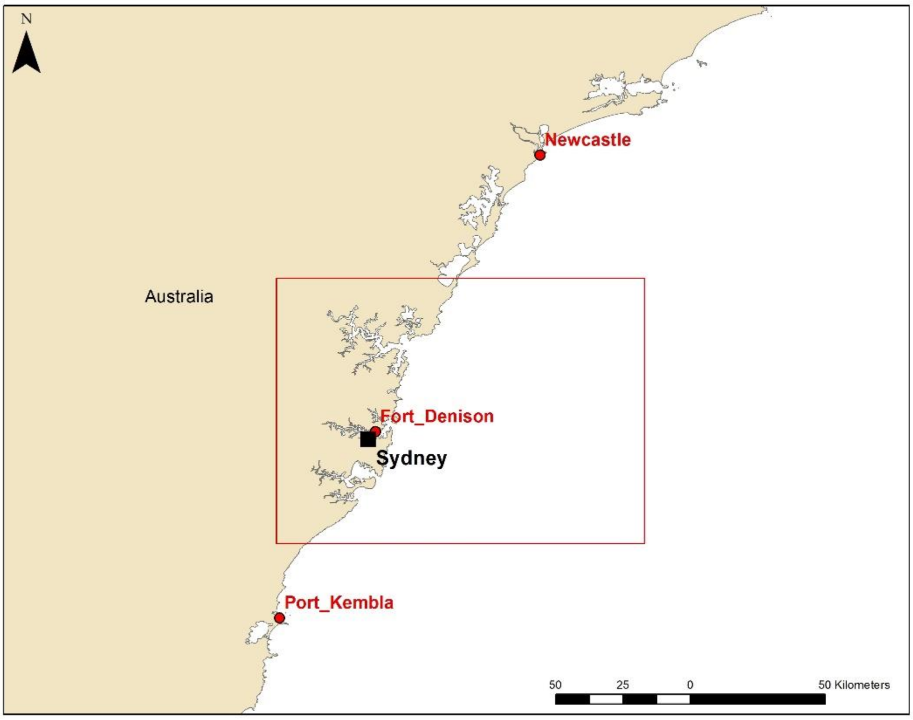
A7: Return Periods NTR Sydney

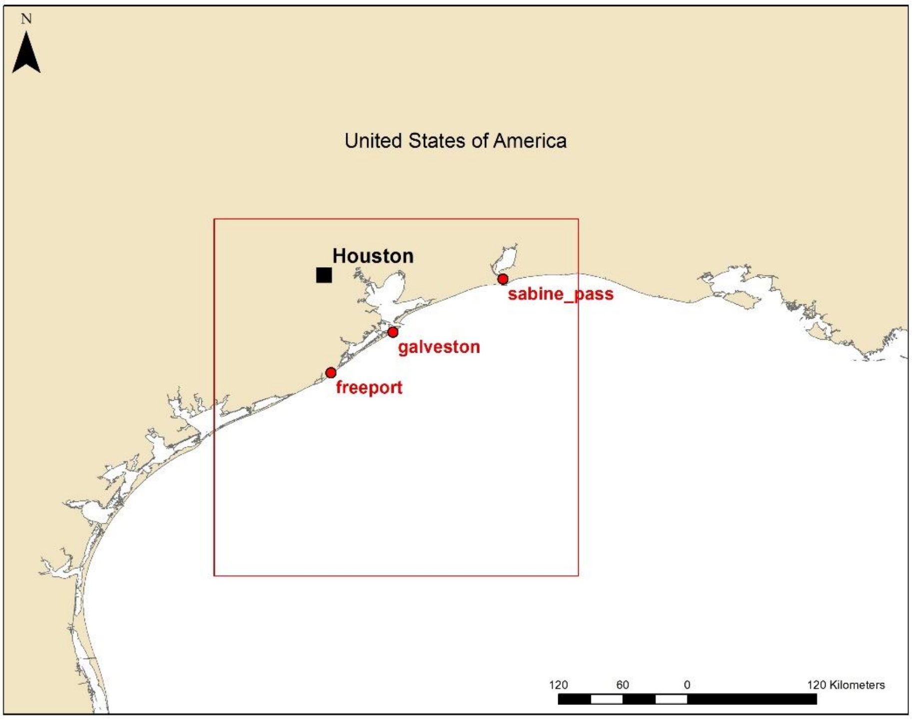




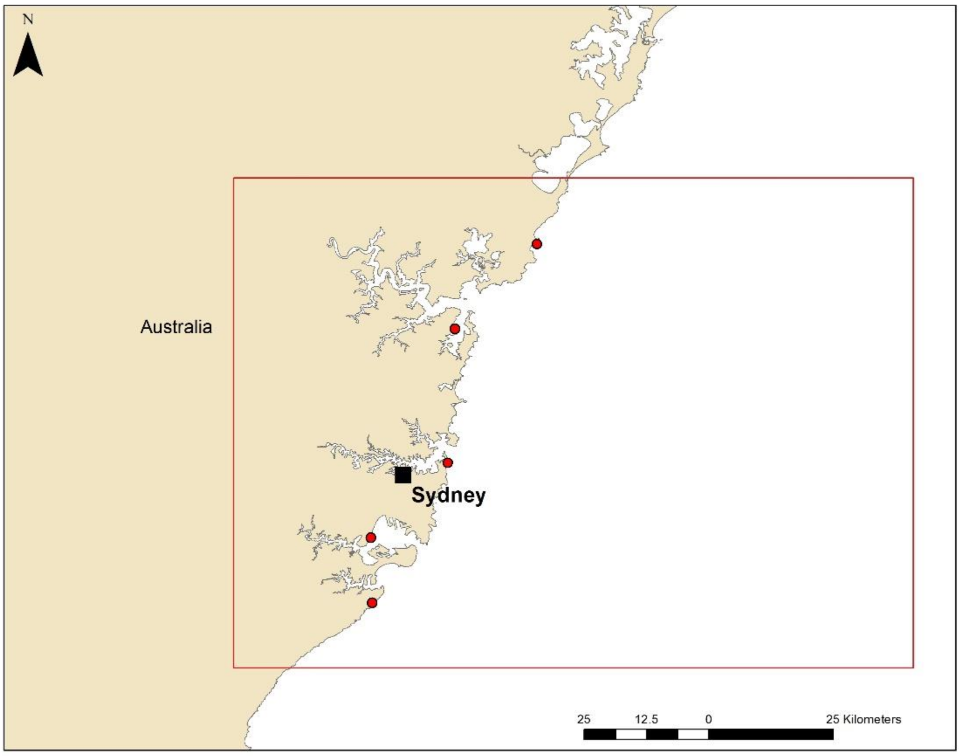


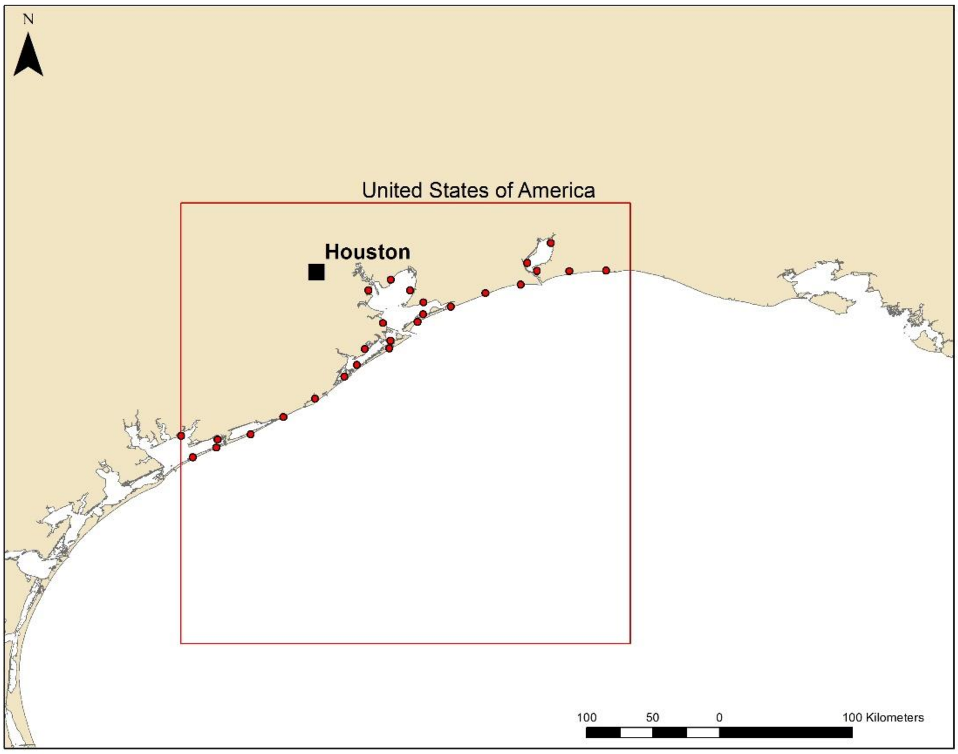
A8: Storm Surge stations (Tadesse & Wahl, 2021) selected for the calculation





Annex 9 Highest Astronomical Tide (Vousdoukas et al., 2018) points for both investigation sites





A10: Highest Astronomical Tide (Vousdoukas et al., 2018) points for both investigation sites

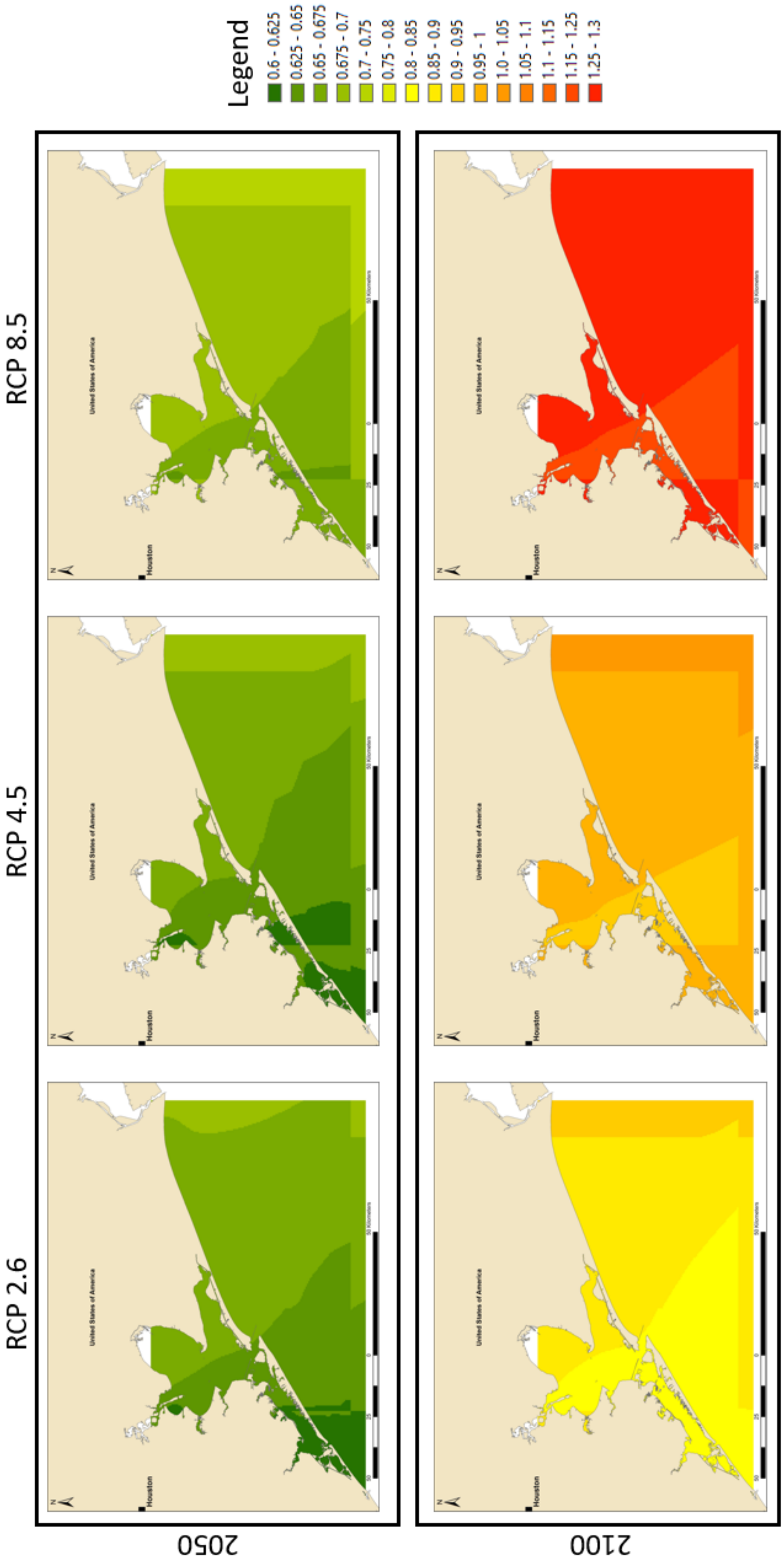
Houston

OBJECTID	latitude	longitude	value5th	valueMedian	value95th
1	29,13632813	-95,08964844	0,162028871	0,217652725	0,298415002
2	29,24987256	-94,86985547	0,174020004	0,229616758	0,313261724
3	29,29964952	-94,86318353	0,173910369	0,229616758	0,312970493
4	28,65521069	-96,2796552	0,139206712	0,197871223	0,277058909
5	28,6298483	-96,0333551	0,143526415	0,199959589	0,277809127
6	28,51079865	-96,20348279	0,138435971	0,197871223	0,276725726
7	28,57522761	-96,04224903	0,142646123	0,199959589	0,277872603
8	28,66569053	-95,81041953	0,143389727	0,199959589	0,278198171
9	28,78248628	-95,58984332	0,14284418	0,199959589	0,277884858
10	28,90684901	-95,37297029	0,16247506	0,217652725	0,298768461
11	29,05712556	-95,1754131	0,162339877	0,217652725	0,298282871
12	29,24542612	-95,03681725	0,162204516	0,217652725	0,298525156
13	29,41982214	-94,91437243	0,173773275	0,229616758	0,31305413
14	29,64265807	-95,01239381	0,161815669	0,217652725	0,298483822
15	29,71341368	-94,86214113	0,208066143	0,26391497	0,351320246
16	29,64275375	-94,73064784	0,208198921	0,26391497	0,350730817
17	29,55919937	-94,63912659	0,208604067	0,26391497	0,351096276
18	29,48088721	-94,64181981	0,208288692	0,26391497	0,351031385
19	29,42698693	-94,68073226	0,208332574	0,26391497	0,351402349
20	29,53160663	-94,45419602	0,208469179	0,26391497	0,350952497
21	29,62274709	-94,22140122	0,208237298	0,26391497	0,351136224
22	29,68116739	-93,98088505	0,212199641	0,266530922	0,35343284
23	29,82815382	-93,93791259	0,211793972	0,266530922	0,353320659
24	29,96112139	-93,77786943	0,227320594	0,281060709	0,366235611
25	29,77304917	-93,8715444	0,212388758	0,266530922	0,353478449
26	29,77083764	-93,65257764	0,227349465	0,281060709	0,365958088
27	29,77625556	-93,40263636	0,227138873	0,281060709	0,366607027

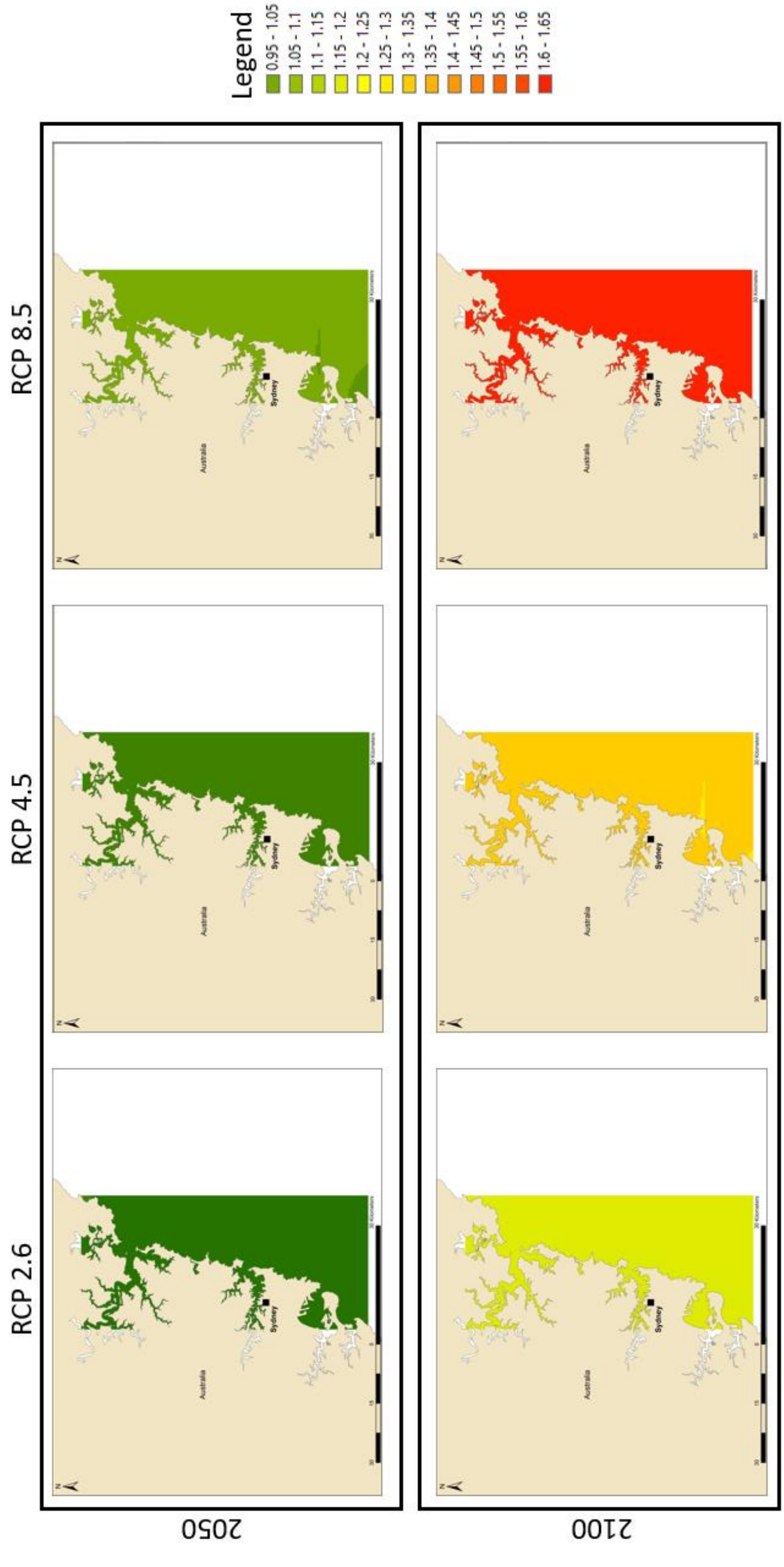
Sydney

OBJECTID	latitude	longitude	value5th	valueMedian	value95th
1	-33,45732324	151,4482475	0,532169519	0,649788271	0,846539047
2	-33,61073275	151,299804	0,534274938	0,649788271	0,848467728
3	-33,85344497	151,2867382	0,529131946	0,643925235	0,840679884
4	-33,98841335	151,1476124	0,528732301	0,643925235	0,839845586
5	-34,10606442	151,1501117	0,522443228	0,634738818	0,826020639

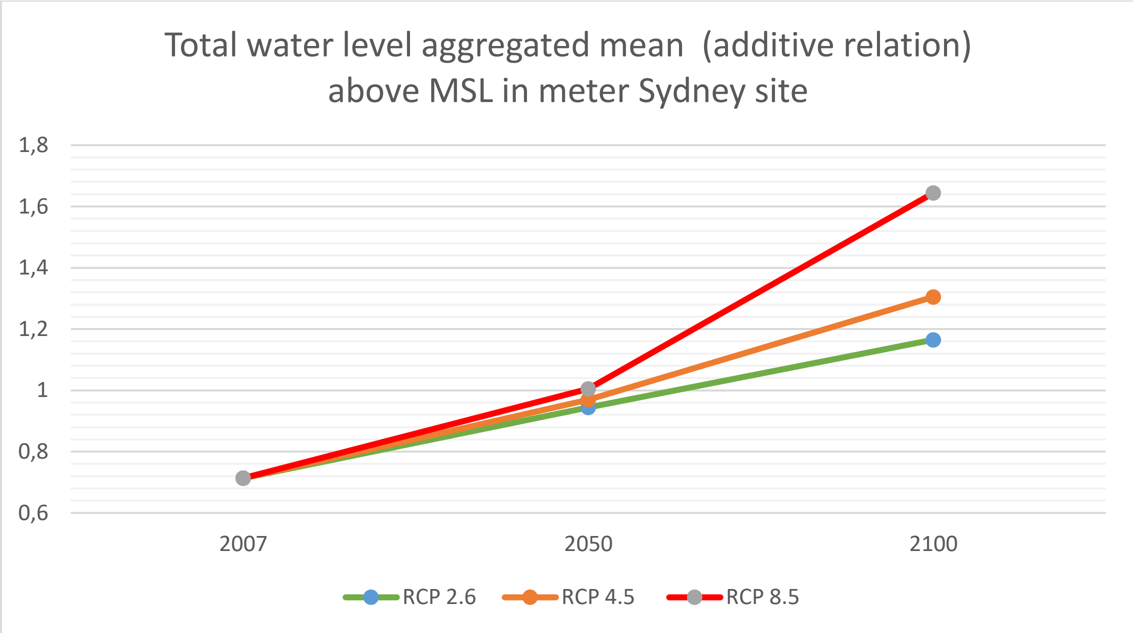
A11: Additive calculation Houston with assigned classes in meters

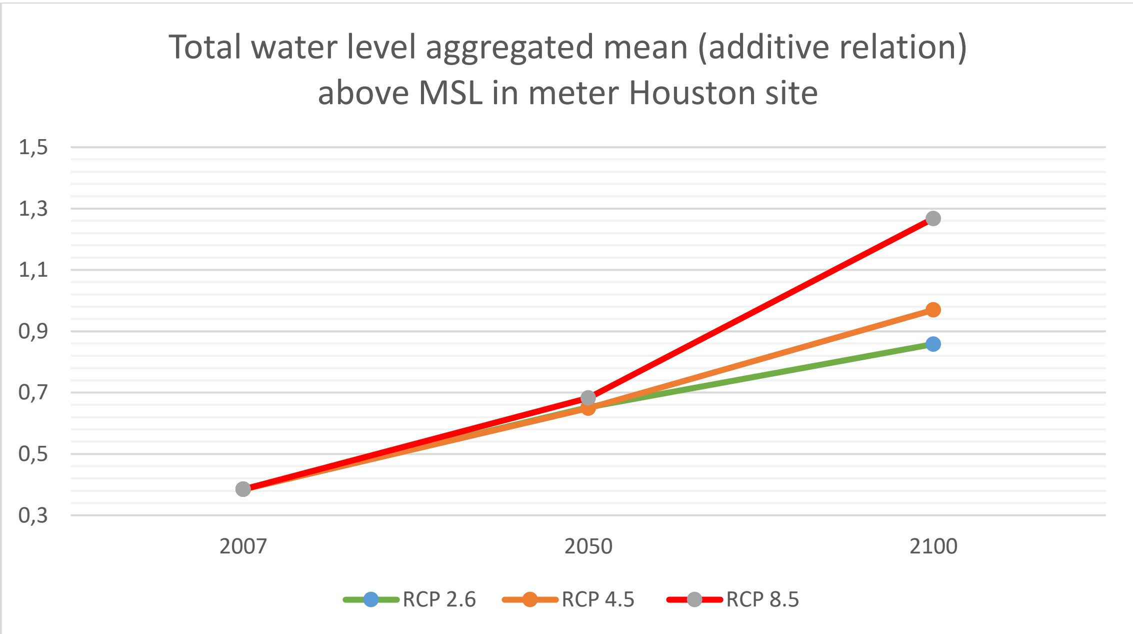


A12: Additive calculation Sydney with assigned classes in meters



A13: Total water level aggregated mean (AM)





A14: Additive model results – mean of raster minimum and maximum

Minimum

Sydney

	2007	2050	2100
RCP 2.6	0,71359636	0,92884207	1,15655911
RCP 4.5	0,71359636	0,96166509	1,30487589
RCP 8.5	0,71359636	0,99587512	1,64381082

Houston

	2007	2050	2100
RCP 2.6	0,38446465	0,61051363	0,81671339
RCP 4.5	0,38446465	0,61323041	0,92702544
RCP 8.5	0,38446465	0,64381438	1,22416639

Maximum

Sydney

	2007	2050	2100
RCP 2.6	0,71359636	0,95031697	1,170336962
RCP 4.5	0,71359636	0,97453094	1,304875894
RCP 8.5	0,71359636	1,00961196	1,643810818

Houston

	2007	2050	2100
RCP 2.6	0,38446465	0,68357408	0,9277400970
RCP 4.5	0,38446465	0,69022006	1,0354001522
RCP 8.5	0,38446465	0,72976911	1,3398950100

A15: STMR model results – mean of raster mean, minimum and maximum

Mean

Sydney

	2007	2050	2100
RCP 2.6	0,713596362	0,948517	1,176767
RCP 4.5	0,713596362	0,975900	1,320692
RCP 8.5	0,713596362	1,011681	1,665720

Houston

	2007	2050	2100
RCP 2.6	0,384464646	0,666733	0,878734
RCP 4.5	0,384464646	0,663785	0,994731
RCP 8.5	0,384464646	0,696943	1,305265

Minimum

Sydney

	2007	2050	2100
RCP 2.6	0,713596362	0,932519	1,162361
RCP 4.5	0,713596362	0,965658	1,302938
RCP 8.5	0,713596362	1,000198	1,624985

Houston

	2007	2050	2100
RCP 2.6	0,384464646	0,616070	0,826134
RCP 4.5	0,384464646	0,61974	0,937983
RCP 8.5	0,384464646	0,650777	1,239262

Maximum

Sydney

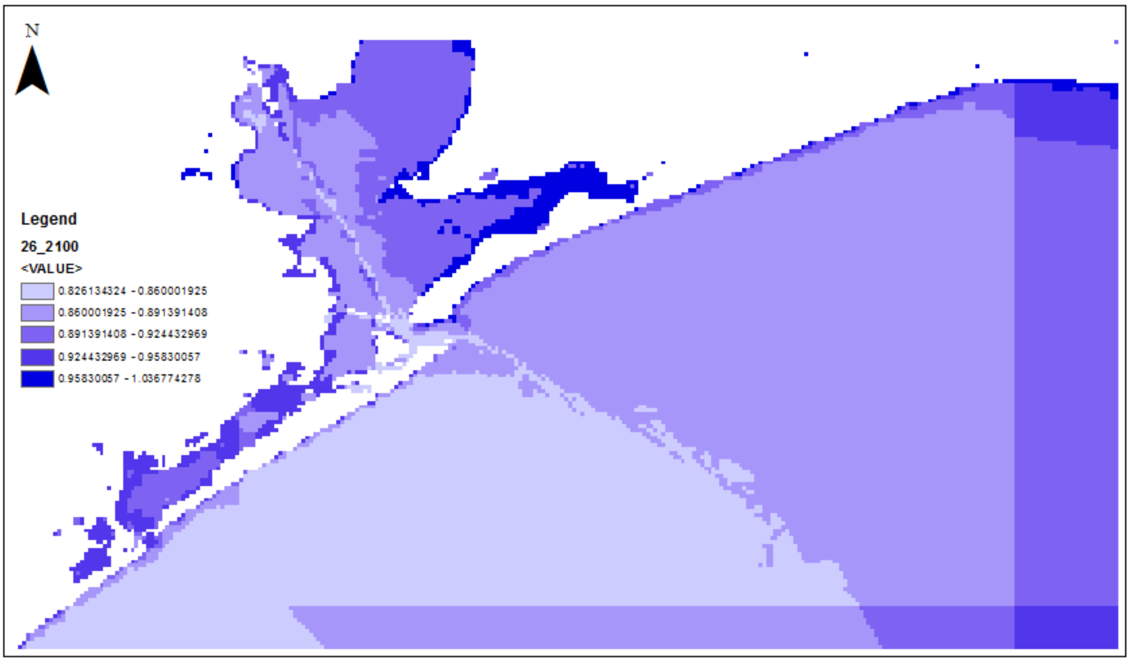
	2007	2050	2100
RCP 2.6	0,713596362	1,099402	1,462359
RCP 4.5	0,713596362	1,141135	1,695548
RCP 8.5	0,713596362	1,197357	2,258369

Houston

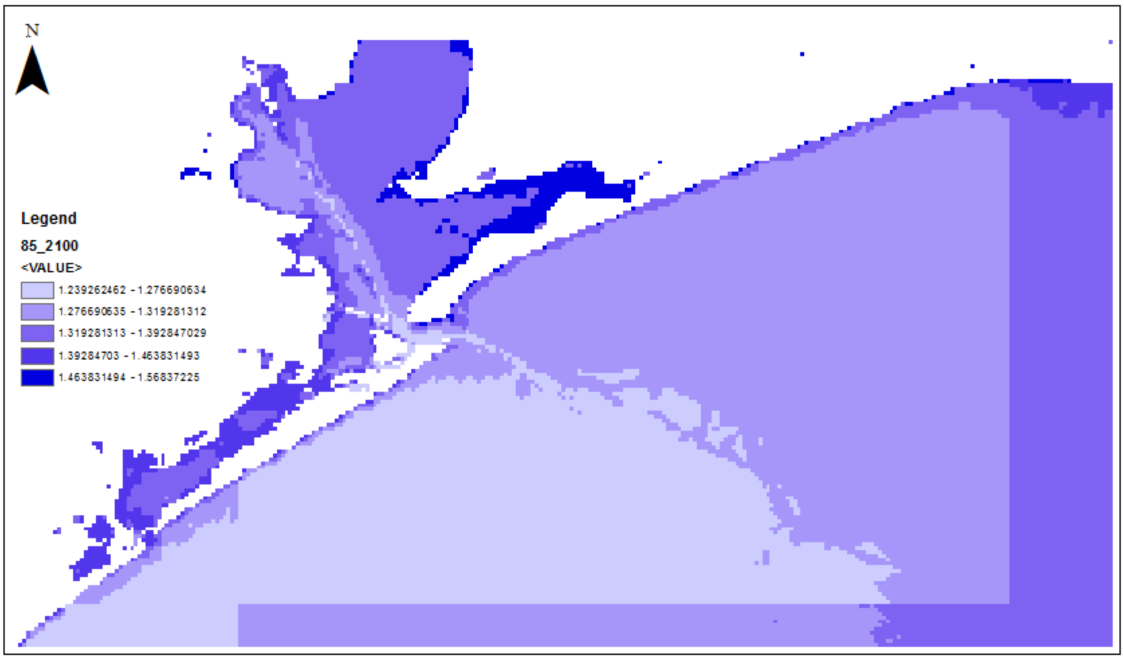
	2007	2050	2100
RCP 2.6	0,384464646	0,746553	1,036774
RCP 4.5	0,384464646	0,753198	1,181506
RCP 8.5	0,384464646	0,806768	1,568372

A16: STMR results Houston

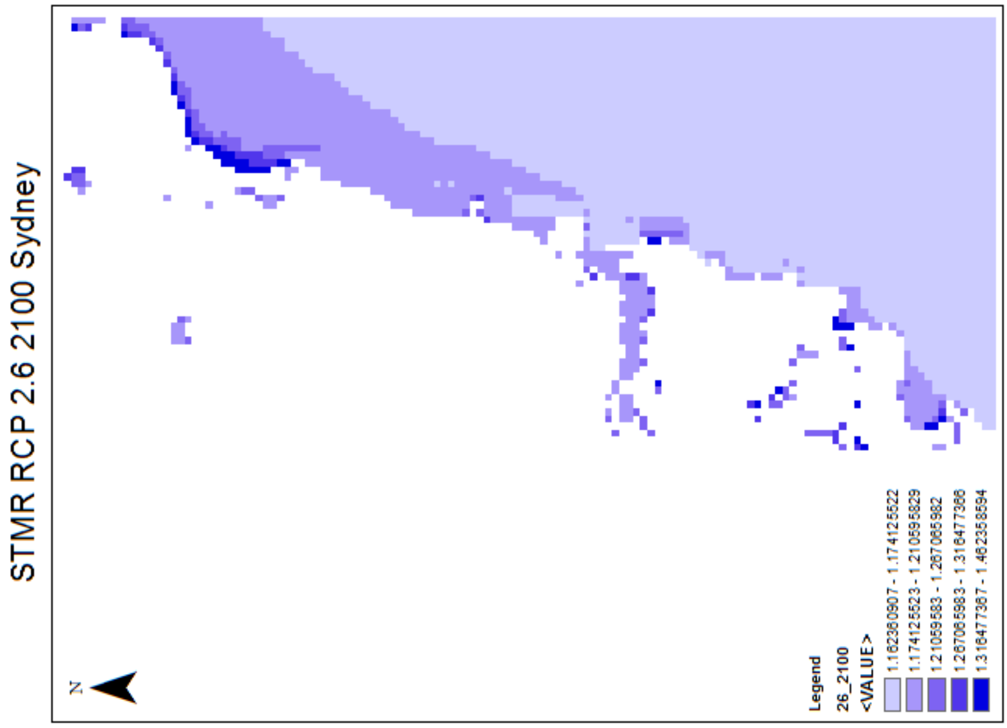
STMR RCP 2.6 2100 Houston

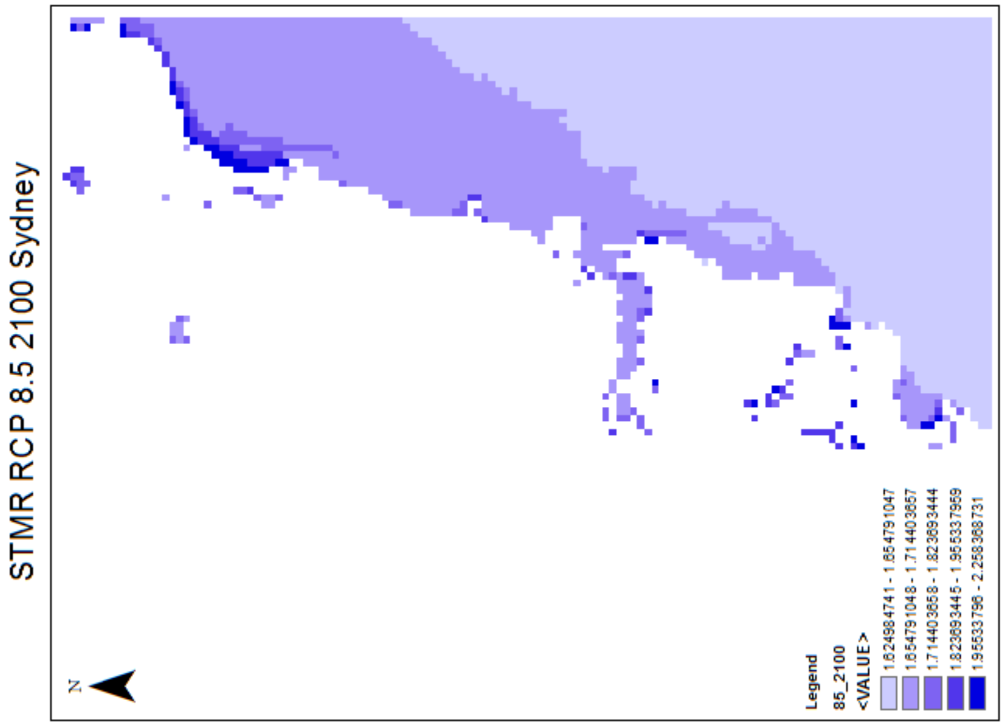


STMR RCP 8.5 2100 Houston



A17: STMR results Sydney





A18: STMadjR model results – mean of raster mean, minimum and maximum

Mean

Sydney

	2007	2050	2100
RCP 2.6	0,7136	0,946426	1,174217
RCP 4.5	0,7136	0,973753	1,317869
RCP 8.5	0,7136	1,009461	1,662278

Houston

	2007	2050	2100
RCP 2.6	0,38446	0,656524	0,865143
RCP 4.5	0,38446	0,652268	0,979421
RCP 8.5	0,38446	0,686249	1,285710

Minimum

Sydney

	2007	2050	2100
RCP 2.6	0,7136	0,93167	1,161359
RCP 4.5	0,7136	0,964777	1,302324
RCP 8.5	0,7136	0,999284	1,623945

Houston

	2007	2050	2100
RCP 2.6	0,38446	0,516807	0,728983
RCP 4.5	0,38446	0,515575	0,844676
RCP 8.5	0,38446	0,547651	1,156310

Maximum

Sydney

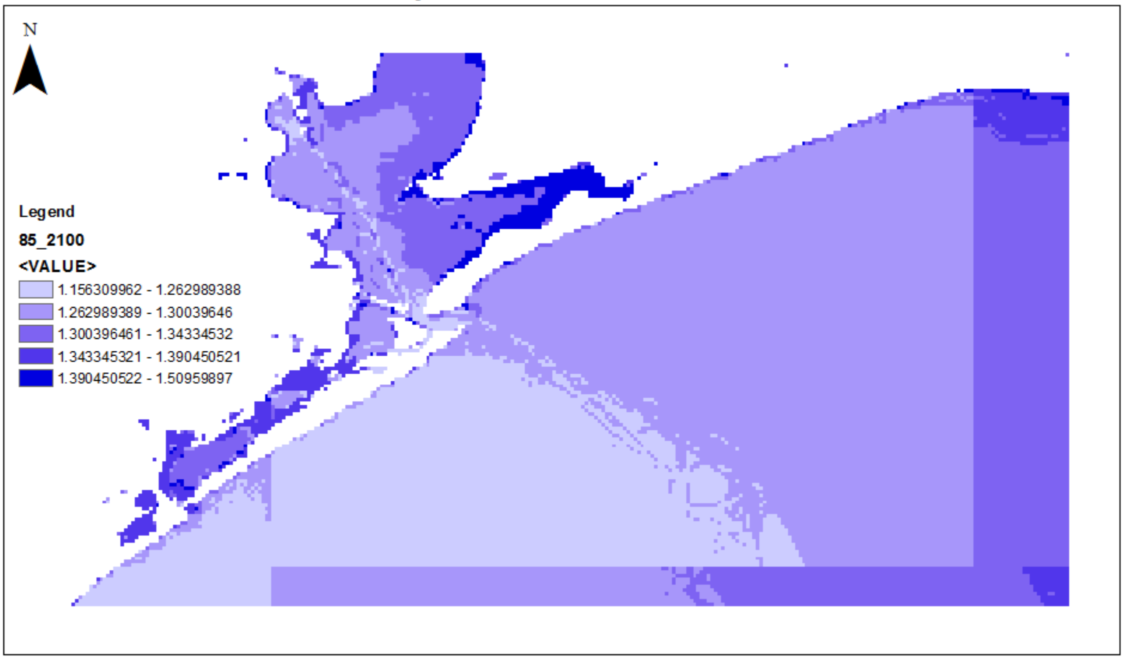
	2007	2050	2100
RCP 2.6	0,7136	1,064111	1,422255
RCP 4.5	0,7136	1,106298	1,653868
RCP 8.5	0,7136	1,161664	2,210623

Houston

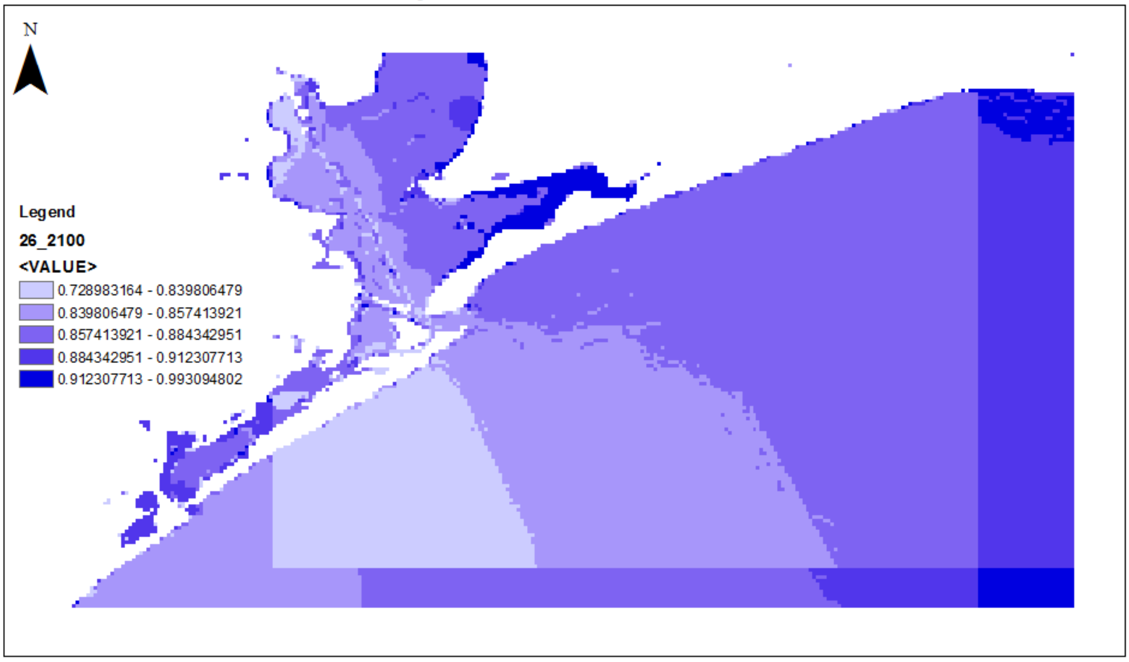
	2007	2050	2100
RCP 2.6	0,38446	0,714309	0,993095
RCP 4.5	0,38446	0,72007	1,133197
RCP 8.5	0,38446	0,771475	1,509599

A19: STMadjR results Houston

STMadjR RCP 8.5 2100 Houston

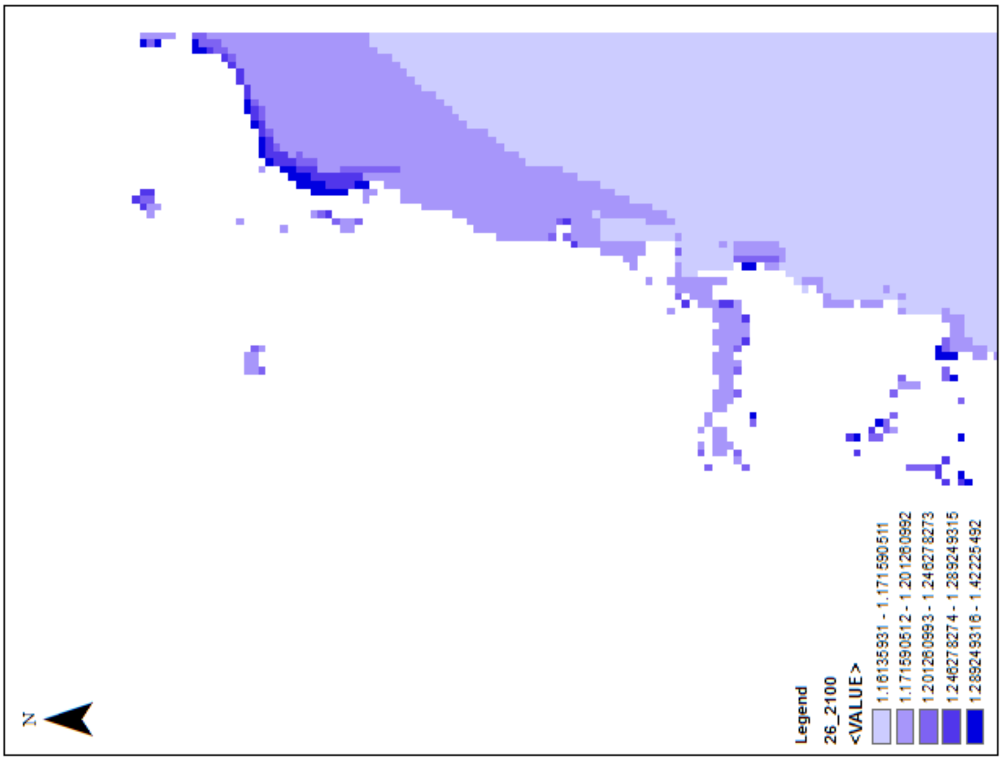


STMadjR RCP 2.6 2100 Houston

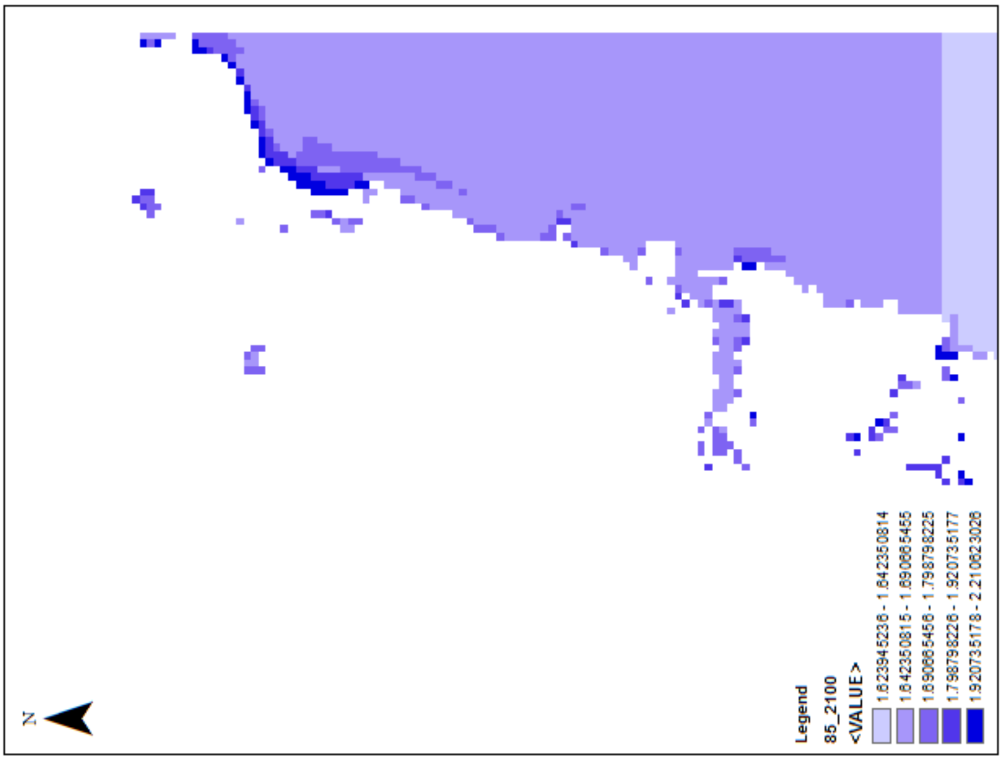


A20: STMadjR results Sydney

STMadjR RCP 2.6 2100 Sydney

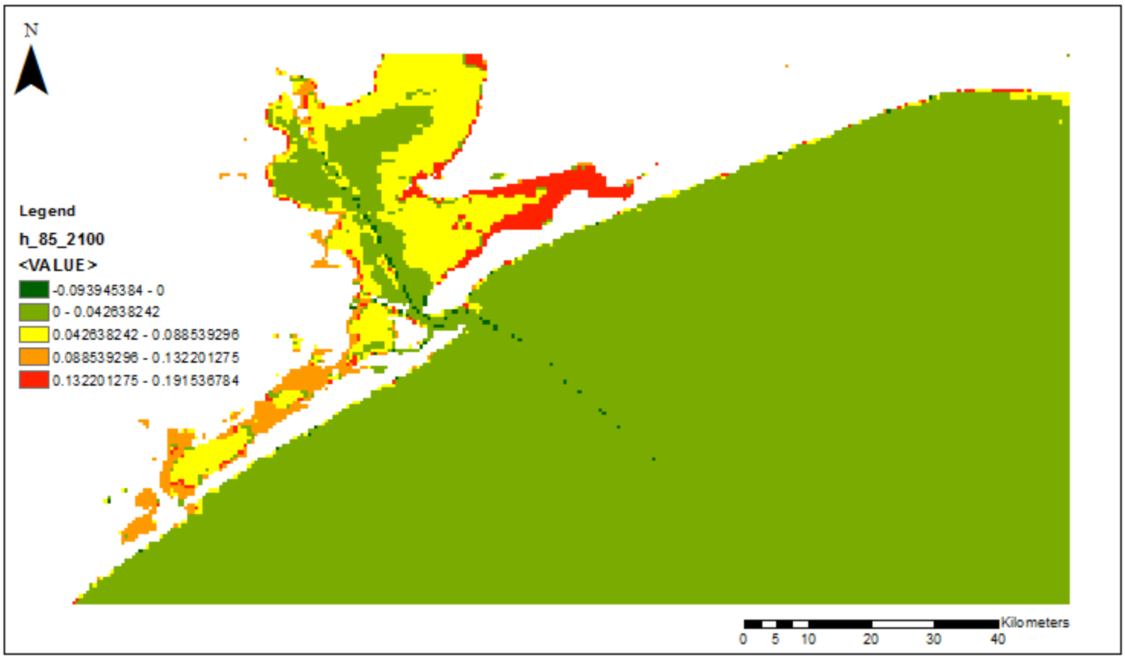


STMadjR RCP 2.6 2100 Sydney

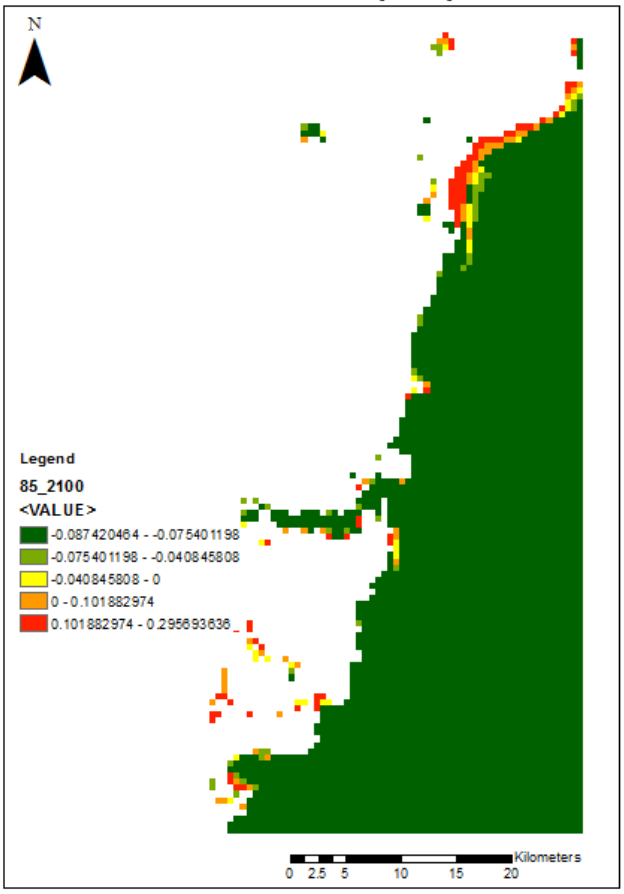


A21: STMR – STMT 15% model difference

STMR - STMT + 15% model difference RCP 4.5 2100 Houston

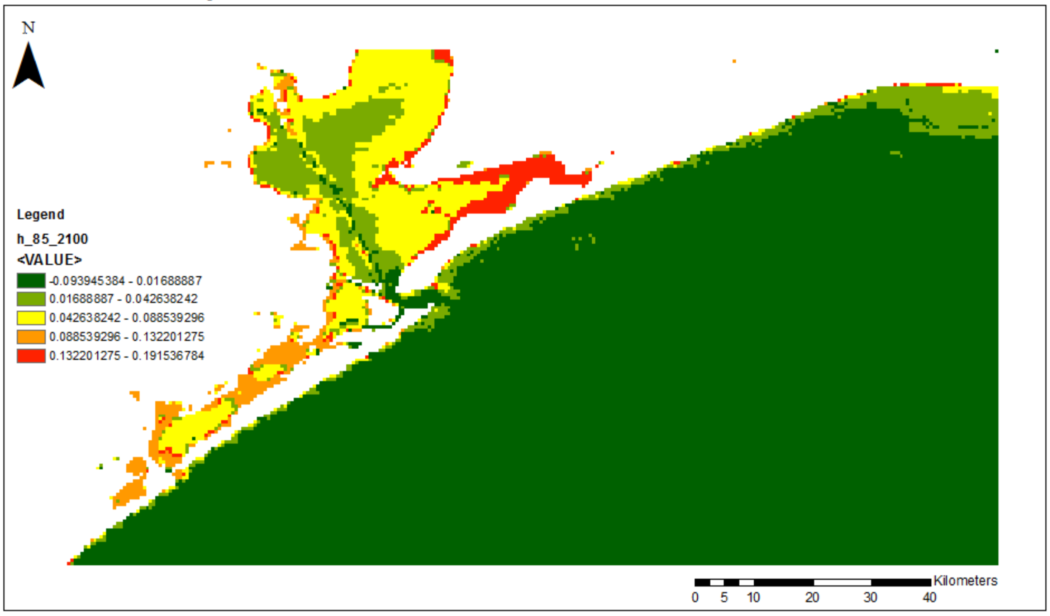


STMR - STMT + 15% model difference
RCP 8.5 2100 Sydney



A22: STMadjR – AM model difference

STMadjR - Additive model difference RCP 8.5 2100 Houston



STMadjR - Additive model difference RCP 8.5 2100 Sydney