Inundated reasoning

With increasing rates of climate change driving sea level rise, **Dr Keqi Zhang** discusses how the quantification of inundation can help improve understanding of the social and economic impacts, and manage the destructive consequences for ecosystems and populations

Firstly, could you explain why you became interested in this particular area?

I have been interested in coastal response to climate changes for a long time. I studied the impacts of sea level rise on Shanghai in 1993 when I worked at the State Key Laboratory for Estuarine and Coastal Research at East China Normal University. In 1994 I went to the University of Maryland to pursue my PhD degree. I was shocked by the number of tourists on the beach and the vast amount of buildings that are so close to the shoreline when I visited the Ocean City, Maryland. As a coastal scientist I feel that I have an obligation to inform people of the risk of living in the low-lying coastal areas so that we can wisely handle the impacts of climate changes on the coast.

How is inundation impact affected by variations in topography and sea level rise acceleration?

The inundation impacts are greatly influenced by the variations in topography. Firstly, in low-lying coastal plains along the US East and Gulf coasts, both built and natural environments are vulnerable to sea level rise inundation. By contrast, the high-relief along the US West coast makes it less vulnerable. Secondly, the distribution of land areas versus elevation has a great effect on the speed of inundation as sea levels rise. The acceleration in sea level rise can amplify the non-linear inundation process, causing the inundation threshold to be reached sooner.

Does Florida have any pre-existing flood management plans in place?

In the US, the major flood management plan is the National Flood Insurance Program (NFIP) for homeowners provided by the Federal Emergency Management Agency. The flood insurance rate of a house is determined by the current occurrence probability of flooding events but sea level rise has not been incorporated into the NFIP. I hope that the NFIP can include the sea level rise effect in the future. This will slow down unwise development in the low-lying coastal areas and help reduce sea level impacts.

Can you provide an insight into the high-resolution digital elevation models (DEM) being used to assess implications of inundation in low-lying areas?

For a given scenario of sea level rise, the magnitude and extent of inundation from a rising sea in a coastal area is determined by local topographic elevations. In the US, topographic elevations are usually derived from topographic maps or digital elevation models (DEMs) provided by the U.S. Geological Survey (USGS). The vertical resolution of traditional USGS DEMs is about 1.5 m for South Florida, which can correspond to kilometres of horizontal distances. We cannot derive reliable inundation extents and processes if these DEMs are used to map sea level rise inundation. As a result, affected population and property cannot be quantified. Fortunately, the advance in airborne Light Letection and Ranging (lidar) technology in the past 15 years has allowed the rapid mapping of topography over a large area with a vertical accuracy of 0.15 m with a horizontal resolution of 1-2 m. DEMs with a much higher vertical resolution can be generated using the lidar measurements. As a result, the magnitude and extent of inundation caused by sea level rise and affected population and property in low-lying coastal areas with gentle slopes can be accurately determined using lidar DEMs.

By what means do you encourage national and international cooperation? How will your research benefit international efforts?

The flooding caused by sea level rise and associated non-linear inundation processes is not unique to South Florida, and is a characteristic of other low relief coastal areas in the US, such as the Mississippi delta, Chesapeake Bay and North Carolina's Pamlico-Albemarle Peninsula, and in other nations eg. the Yangtze River delta in China. To mitigate the societal impacts of the non-linear inundation process in these low-lying areas, detailed monitoring, mapping and modelling of sea level impacts, research on the human carrying capacity and resiliency of limited high land areas, and comprehensive planning for relocating population, economic foci and endangered species in response to various scenarios of sea level rise need to be undertaken through national and international cooperation. My research on South Florida provides the methods and a sample for studying the impacts of sea level rise on land area, population and property in other low-lying areas.

A rising concern

A study of inundation impacts by the **International Hurricane Research Center** at Florida International University promises to raise awareness of how this increasing trend could affect land masses and populations

AT THE END of 2012 the East coast of America was dealing with the aftermath of the biggest storm ever to hit the coastline: Hurricane Sandy. Our ability to prepare for extreme weather events will inevitably have to increase over the coming years as incidents become more frequent. In Florida alone, sea level rise has risen by 8 inches over the last 100 years and if this continues, the year 2060 could see this figure reaching 12 inches, according to the US Army Corps of Engineers. Industrial activities and entire countries can be affected by these changes but the magnitude of impact has always been difficult to predict. To address the shortcomings in current knowledge, researchers at the International Hurricane Research Center at Florida International University are equipping policy makers with the tools to make science-based decisions that could change the way we prepare and protect our valued coastlines.

THE TECHNIQUES

Accepting a rising sea level as an inevitable consequence of climate change, the leader of the team, Dr Keqi Zhang, is committed to raising awareness amongst policy makers in Florida and encouraging governments to pay more attention to these changes. In order to generate more interest, Zhang has brought a dedicated focus to the effects of sea level rise and has greatly advanced our understandings of inundation, the process whereby land becomes covered with water. Inundation has the potential to greatly affect both human and ecological behaviour by drowning crops and damaging property. Zhang's research uses the region of South Florida to illustrate how this process can be modelled, with the view to prompt action from policy makers. To alert both federal and state governments to the potential severity of inundation impacts, and to allow policy makers to make better decisions, Zhang and his group have used various data collection and modelling tools to accurately examine how inundation will affect both human endeavours and ecological behaviour. By embracing innovative Light Detection and Ranging (lidar) and geographic information system (GIS) techniques, the team has worked to derive a new, high quality digital elevation model (DEM). This technical approach promises to be particularly useful in gauging the potential impacts of inundation as it combines information gathered by scanners on-board aircraft with algorithms designed to separate land from trees, buildings and other structures, ultimately generating accurate results necessary for modelling how land will respond to flooding. Throughout this process, Zhang's group have constantly endeavoured to understand the severity of the situation and develop strategies to assist society in being best prepared for adaptation.

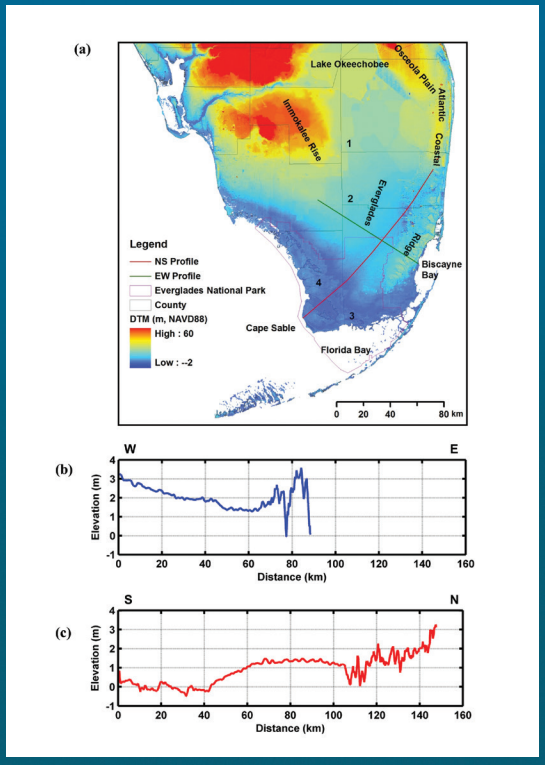
NON-LINEAR SCALE

At its very core, Zhang's research hinges on an understanding that the link between sea level rise and inundation is a nonlinear process, an understanding that is set to play an important part in alerting policy makers to act swiftly. The researchers in Florida have observed that a low-end sea level rise does not make a great difference to land, but once the rise hits a certain tipping point the region will witness drastic consequences. Zhang maintains that the assumption that there will be a steady stream of problems to match a steady rise in sea level has bred a mood of complacency amongst decision makers: "The slow inundation process occurring prior to the tipping point can give people the false impression that sea level rise does not cause problems, whereas the rapid inundation after the tipping point limits the adequacy of a late response". Reinforcing this view, he has plotted hypsometric curves that indicate the effect that different elevations have on land. For relatively flat, low-lying areas, such as Florida, these graphs show that a marginal increase beyond a tipping point has the potential to easily overwhelm a region.

SPECULATION

Following on from his important argument – that the effects of sea level rise on inundation impacts are nonlinear – Zhang has developed a series of predictions and policy suggestions based on different steps of sea level rise. Crucially, believing that a single set of policies would be insufficient, the team at the International Hurricane Research Center has brought a level of flexibility into their speculations to account for the uncertainty surrounding levels of sea level rise in the future and to meet their key objective of enabling policy makers to be more prepared for whatever changes might occur. In Florida, the potential effects has been summarised thus: "A 0.5 m sea level rise will affect 12,000 people and US $3 billion of real property; a 1.0 m sea level rise will affect 113,000 people and US $35 billion of real property; and a 1.5 m sea level rise will affect 512,000 people and $129 billion of real property". Zhang's scale

Zhang, K. 2011. Analysis of non-linear inundation from sea-level rise using Lidar data: a case study for South Florida. *Climatic Change* 106:537-565.



QUANTIFICATION OF INUNDATION IN SOUTH FLORIDA CAUSED BY SEA LEVEL RISES AND ITS SOCIAL AND ECONOMIC IMPACTS

OBJECTIVES

- To create high-resolution DEMs for South Florida using lidar measurements; develop methods in GIS to estimate land areas inundated by potential sea level rise; and quantify impact on the real property, population, and critical infrastructure
- To examine the effect of topography and acceleration in sea level rise on inundation, identify patterns and seek a tipping point in the inundation process
- To examine the non-linear interaction of storm surge and sea level rise through numerical modelling to compute the surge flooding under various sea level rise scenarios

KEY COLLABORATORS

National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center US Fish and Wildlife Service and The Nature Conservancy

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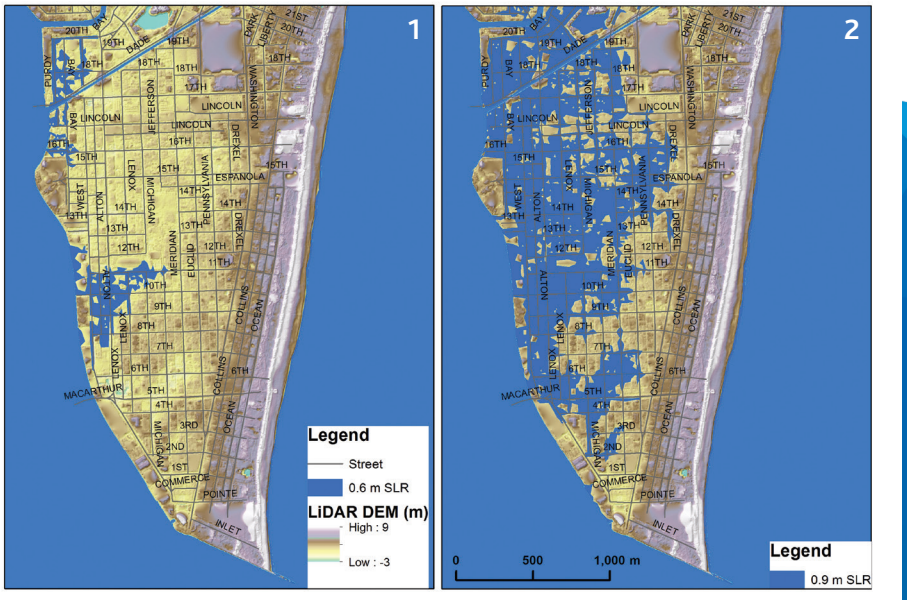

Inundations caused by 0.6 m (1) and 0.9 m (2) sea level rise in South Beach/Miami Beach. The area between 8th and 11th streets along the Alton Road will be underwater if the sea level rises by 0.6 m. About 1,300 residents (excluding visitors) in South Beach will be affected (inundated) for a 0.6 m sea level rise scenario in terms of 2010 census data. The affected property value is about US $250 million in terms of the 2007 property just value. The vulnerability of this area to inundation was demonstrated by a flooding event caused by heavy rain on June 5, 2009. The affected population and property value are 11,000 and $2.2 billion ($2,200 million), respectively, for a 0.9 m sea level rise.

of responses will enable the group to work with policy makers to calculate methods of action that can complement a scale of potential devastation.

FLORIDA

Zhang's research has been incredibly informed by an in-depth study of four counties in south Florida: Monroe County, Miami-Dade County, Broward County and Palm Beach County. As they form a low-lying land mass largely sitting just a few meters above sea level, these counties are especially vulnerable to the tipping point. Rich in environmental resources, culture and industry, they also make an invaluable case study for understanding the natural and economic consequences of a sea level rise above the tipping point. South Florida is an exceptionally vulnerable area of the US which needs dedicated research to best prepare coastal citizens of potentially devastating future change. Confident that the value of affected property and economic activities is a core measurement for understanding climate change, the team has sought to quantify the value of real estate in the area that would be threatened by a rising sea level.

EVERGLADES NATIONAL PARK

As well as considering the threat to homes and communities, Zhang's research also contemplates the Everglades, a national park with a delicate ecosystem that depends on flows of freshwater taken from the Kissimmee River and Lake Okeechobee. By exhibiting such a sensitive balance between salt and fresh water, the Everglades indicates that a rise in sea level will have knock-on consequences that go beyond flooding. Remarking on a governmental plan recover the Kissimmee- Okeechobee-Everglades ecosystem in the next 30 years in an ambitious $8 billion programme, Zhang argues that both federal and state governments must consider the extent and process of inundation on this delicate ecosystem and factor this into their scheme, articulating that: "The objectives of the comprehensive Everglades restoration plan also have to be adjusted or even abandoned for the high-end scenarios of sea level rise".

> Zhang has brought a dedicated focus to the effects of sea level rise and has greatly advanced our understandings of inundation

FACILITATING CHANGE

Federal, state, county and municipal governments need to work together with coastal residents to develop plans and strategies for mitigating the effects of sea level rise. Facilitating efficient policy is key to Zhang's work and it is hoped that a drastic mitigation and response plan that accounts not only for the magnitude of potential changes, but also for their variety, will arise from his continued research. Some of the suggested responses for Florida are radical, such as moving the state's endangered species, population and economic core to more elevated areas. Through the deliverance of accurate and flexible research, Zhang and his colleagues are playing a significant part in equipping policy makers with the knowledge that will enable them to conduct this large-scale task with efficiency.