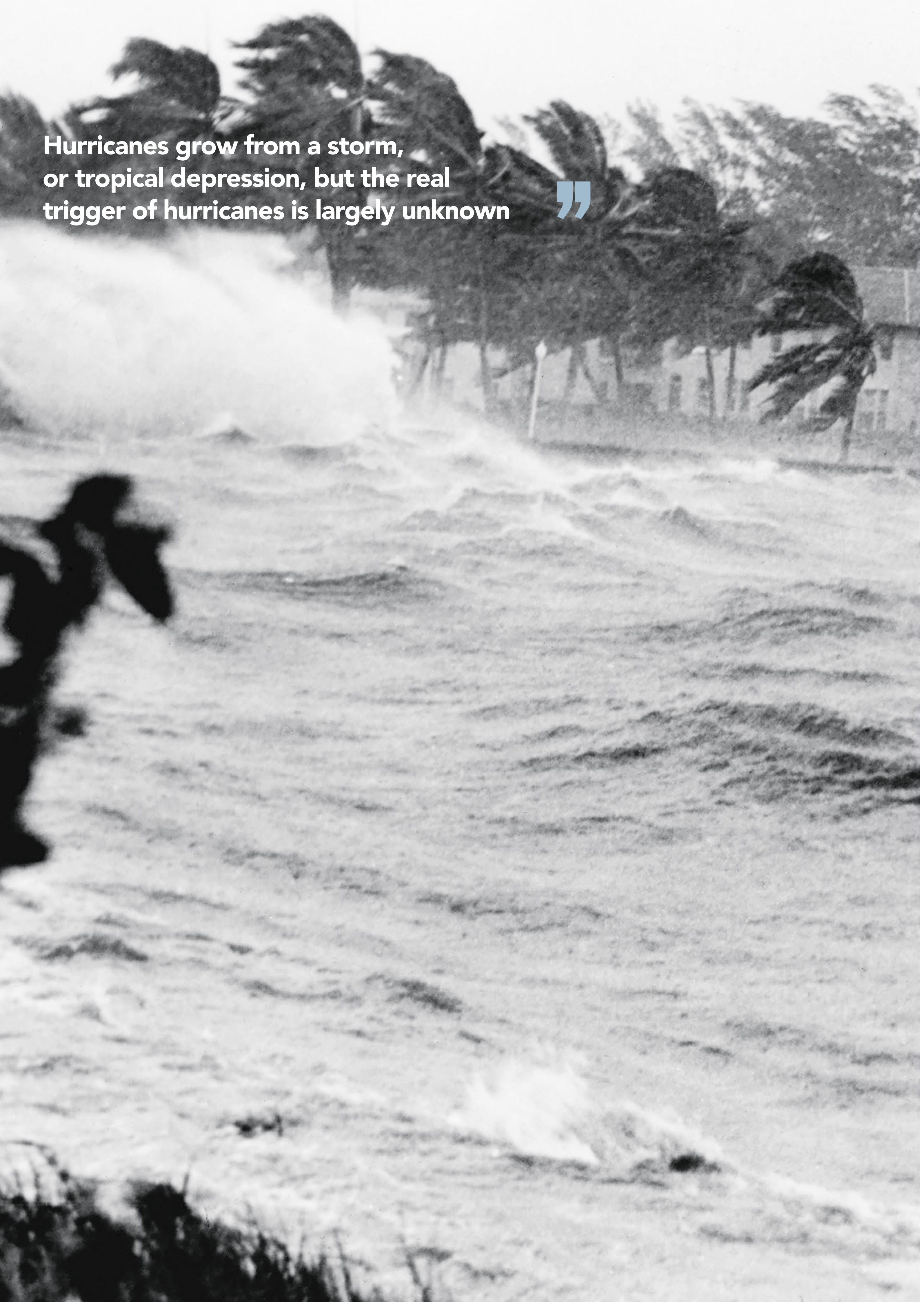


Hurricanes grow from a storm, or tropical depression, but the real trigger of hurricanes is largely unknown

Predicting and preparing for hurricanes

Ning Lin is an Assistant Professor at Princeton University, who is advancing hurricane and climate science, by refining methods in risk analysis. In a collaborative project, her team are developing models to better predict how hurricane frequency, intensity and size alter in a changing climate. This is vital for helping us understand more about the potential hazards and risks facing us in the future, such as those associated with climate change.

The term tropical cyclone describes a rotating system of clouds and storms, occurring over oceanic waters. Once they reach a particular speed they can be classified as a severe cyclone, typhoon or hurricane – depending on their origin. Hurricanes grow from a storm, or tropical depression, but the real trigger of hurricanes is largely unknown. 'Land-fall' hurricanes that make their way over land are particularly catastrophic, and are associated with strong winds, heavy rainfall, coastal erosion and storm surges. Storm surges result in a rising of the sea level above the normal tide level, largely driven by wind, pressure, ocean depth and land topography. Associated flooding causes the greatest destructive threat to infrastructure and life. Climate change has resulted in increases in both sea level and water evaporation, adding power to these events. Flooding is expected to be one of the most economically devastating impacts of climate change, having occurred alongside catastrophic hurricane impacts in the USA, such as Hurricane Katrina in 2005, Hurricane Sandy in 2012, and Hurricane Harvey in 2017. While there are numerous coastal locations at risk of hurricane impacts, Professor Ning Lin and her colleagues are finding solutions to predict and prepare for these events.

MODELLING FUTURE RISK

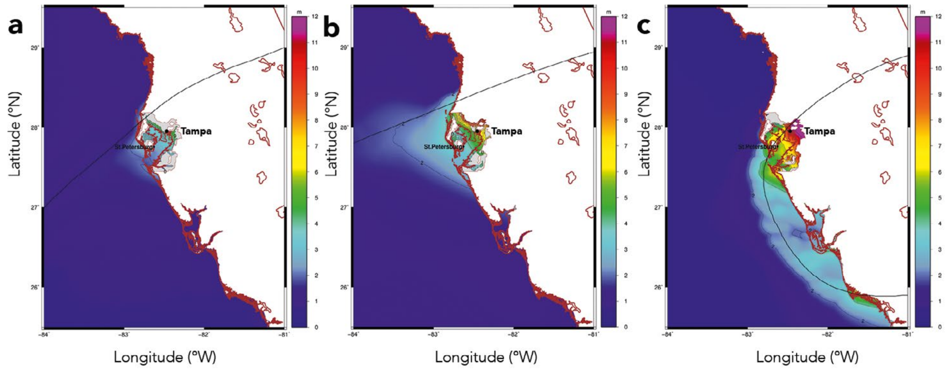
Prof Lin combines engineering, science and policy to study weather extremes associated with tropical cyclones, to predict their behaviour and impact. She is currently leading a collaborative project to refine hurricane risk analysis. While the results will be valuable to all coastal areas that may be affected by hurricanes, the project focuses on case studies in vulnerable locations such as New York, New Jersey, North Carolina and Florida in USA and Shanghai in China. By comparing tropical cyclone hazards in these locations, and considering how they may develop in the future, their work helps to build strategies in engineering and policy.

Previously, predictions were made based on historic records of storm activity. Today, scientists use modelling techniques combining environmental data to predict likely future outcomes. Modelling storm activity is a complex challenge; many factors must be considered such as moisture, wind, and temperature in the atmosphere and thermal condition of the upper ocean. The team have been investigating hurricane behaviour by modelling their potential track movements, intensity and size within set climatic conditions. Hazards and risks are deduced using predictions of how storms 'fall' upon the land. This approach was used to analyse various coastal sites such as NYC and Tampa in Florida, where the results suggested an increase of surge floods occurring in the future, as a result of climate change.

HURRICANE SANDY

In studies published in 2010 and 2012, Prof Lin and colleagues found NYC to be highly vulnerable to hurricane storm surge due to its geographical location – at the vertex of the right angle that is formed by Long Island and New Jersey (NJ) – and due to climate change.

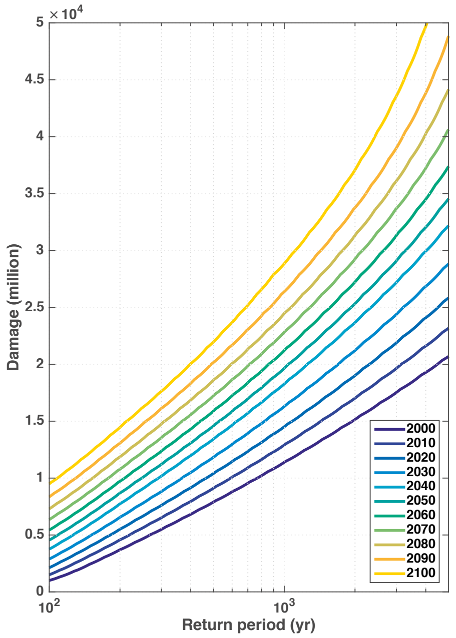
In 2012, Hurricane Sandy flooded the USA East Coast with extreme storm surges, as the storm tide reached a record height of 3.44 m. In a 2016 analysis, Prof Lin and colleagues further considered the effect of sea-level rise. Retrospectively, they summarised that surge flooding risk for NYC increased in the last millennium due to sea level rises and shifting storm activity. They also found the frequency of Hurricane Sandy-like extreme flood occurrences had increased in the previous two centuries. It is even more likely to rise throughout the 21st century due to the relationship between sea level and climate.



The 1921 Tampa hurricane compared with two grey swan TCs. a) The 1921 Tampa hurricane simulated based on observed storm characteristics. Simulated surge at Tampa is 4.0 m. **b)** The 'worst' surge (5.9 m) event for Tampa in the NCEP/NCAR reanalysis climate of 1980–2005. **c)** The 'worst' surge (11.1 m) event for Tampa in the 2068–2098 climate projected by HADGEM for the IPCC AR5 RCP8.5 emission scenario. The shaded contours represent the simulated surge height (m; above MSL) and the black curve shows the storm track. Originally published in Lin, N. and K.A. Emanuel (2016). Grey swan tropical cyclones. *Nat. Clim. Change.* doi:10.1038/nclimate2777

HURRICANE HARVEY

The team have also developed methods to estimate hurricane rainfall and flood hazards under climate change. In 2017, Hurricane Harvey produced the largest rainfall of any US hurricane on record and flooded much of the Houston metropolitan area. Prof Lin's colleague Dr Kerry Emanuel (Massachusetts Institute of Technology) estimated that the annual probability of 500 mm of rainfall (similar to Harvey) somewhere in the state of Texas, which was about 1% in the period 1981–2000, will increase to 18% in 2081–2100. Other team members, including Drs James Smith (Princeton), Gabriel Vecchi (Princeton), and Thomas Knutson (NOAA/GFDL), also found that climate change will increase hurricane rainfall through changing the moisture content of the atmosphere and altering storm activity, including changing the so-called extratropical transition pattern of the storms.



Estimated building damage as a function of return period for NYC for years 2000–2100, based on projected building stock growth, RCP4.5 relative sea-level rise scenario, and composite storm tide climatology. Originally published in Lin, N. and E. Shullman (2017), Dealing with hurricane surge flooding in a changing environment: part I. Risk assessment considering storm climatology change, sea level rise, and coastal development. *Stochastic Environmental Research and Risk Assessment*, doi: 10.1007/s00477-016-1377-5

SPLASH OF THE GREY SWAN

Not all of these occurrences can be predicted; extremely unlikely, unanticipated events are referred to as "black swans". Together, Professors Lin and Emanuel have defined "grey swan" tropical cyclones as the unexpected events which can be somewhat predicted. These are high impact storms which would not be predicted based on the history alone, but by integrated present-day physical knowledge. While the unexpected "black swans" are extremely hard to predict, their grey cousins can be better prepared for. As discussed in their 2015 publication in *Nature Climate Change*, they estimated 'grey swan' tropical cyclone storm surge threats along three vulnerable coastal regions. Unexpected threats were identified for the Persian Gulf and greater threats than expected emerged for Cairns, Australia and Tampa, Florida, potentially requiring additional hazard considerations in these areas.

DEFENDERS OF THE COAST

For coastal communities facing the danger of flooding, a resilient built and natural environment is needed. This can be achieved by combining aspects of mitigation, engineering, and local politics. Prof Lin collaborates with colleagues of varied skill sets, such as Michael Oppenheimer, a Professor of Geosciences and International Affairs at Princeton, Guy Nordenson, an Architecture Professor at Princeton, and Howard Kunreuther, who is a Professor of Decision Sciences and Business and Public Policy at the Wharton School. Oppenheimer studies science and policy of the atmosphere, particularly climate change and its impacts. He and colleagues have investigated the amplification of flood frequencies due to local sea level rise, flood implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilisation targets, and related policy issues. Nordenson leads a 'Structures of Coastal Resilience' study that incorporates hurricane and climate science into engineering design for coastal resilience. Kunreuther leads the insurance policy research of the project. For houses at risk along the coast of the USA, The Federal Emergency Management Agency (FEMA) has an insurance programme in place. FEMA recommends that the houses be elevated to at least one foot above the base flood elevation level, though Professors Lin and Kunreuther question this, stating that this recommendation lacks specific guidelines. Together they propose another option – an economically optimal elevation level (OEL) that is estimated through a cost-benefit analysis.

PROJECTING THE FUTURE

Prof Lin and her collaborators are developing a theoretical risk assessment framework, which combines physical data with statistics to simulate storms' activity, hazards and risk. They discuss how hazards associated with hurricanes are all interrelated, so many factors should be taken into account when predicting these events. There is also a role to play for politics, such as urban planning and federal and insurance bodies in coastal risk mitigation, who should find systematic strategies to prepare for potential hazards. The team highlight a need for appropriate policies and precautions to be in place for extreme events which might occur in the future, with the onset of climate change.

Q&A

Could your methods and approaches benefit other researchers across the world?

Yes, tropical cyclones happen in many coastal areas around the world. Our methodologies are generally applicable and we have applied them to many locations in the USA, China, and Australia.

Do you have hope that modelling techniques may become refined in the future, so that extreme events may become more predictable?

Yes, better predicting the extremes is the goal of improving risk analysis. As we understand the physical mechanisms of the storms better and as more powerful computational resources become available, we will be able to better predict extreme tropical cyclones in different time scales. And we aim to continue incorporating that improvement on storm prediction or projection into hazard analysis and risk management.

How unique is the approach in considering the interrelationship of hazards in risk mitigation?

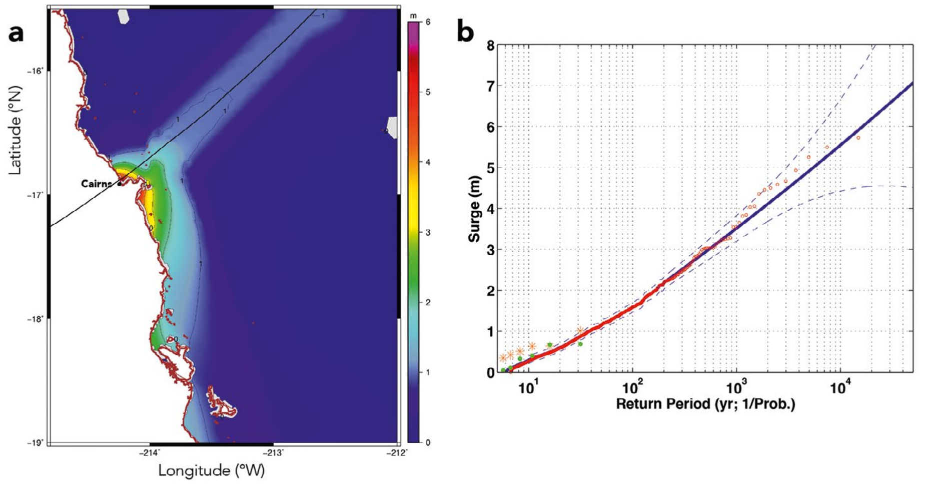
Hurricane hazards (strong wind, storm surge, and heavy rainfall) are physically correlated. We explicitly model this physical correlation of the hazards, and we have also integrated the joint hazard model with the storm climatology model to investigate how these hazards will jointly vary in a changing climate. Such understanding will help develop advanced, possibly multi-purpose risk mitigation strategies.

How can coastal cities better prepare for future hazards associated with climate change?

Coastal cities may incorporate the projection of future climate change effects, such as those developed in our project, into their long-term planning, in order to maintain desired reliability and resilience over time. This is also called climate adaptation.

What lies ahead for your project?

Relatively large uncertainties still exist in the climate projection and thus the hazard projection. We should continue to improve the models and reduce model uncertainties. On the other hand, we should better account for the inherent uncertainties when developing risk mitigation and climate adaptation strategies. Both reducing uncertainties and accounting for uncertainties in meaningful ways require novel approaches.



Storm surge risk analysis for Cairns, Australia, based on 2,400 synthetic events in the NCEP/NCAR reanalysis climate of 1980–2010. The associated annual frequency for the synthetic events is 0.16. **a)** The 'worst' surge (5.7 m) event for Cairns. The shaded contours show the simulated surge height (m; above mean sea level) and the black curve shows the storm track. **b)** Estimated storm surge level as a function of return period for Cairns. The red dots show the synthetic data, and the dash curves show the 90% statistical confidence interval. Orange dots show the six storm surges in Cairns between 1980 and 2010; green dots show the modelled surges for these historical TCs (the annual frequency of the historical storms is 0.19). Originally published in Lin, N. and K.A. Emanuel (2016). Grey swan tropical cyclones. *Nat. Clim. Change.* doi:10.1038/nclimate2777

Detail

RESEARCH OBJECTIVES

Professor Ning Lin's current research integrates science, engineering, and policy to study tropical cyclones and associated weather extremes (e.g., strong winds, heavy rainfall, and storm surges), how they change with climate, and how their impact on society can be mitigated.

FUNDING

National Science Foundation (NSF): EAR-1520683

COLLABORATORS

James Smith (Princeton), Kerry Emanuel (MIT), Howard Kunreuther (UPenn), Thomas Knutson (NOAA/GFDL), Guy Nordenson (Princeton), Gabriel Vecchi (Princeton), and Michael Oppenheimer (Princeton).

BIO

Ning Lin is an Assistant Professor of Civil and Environmental Engineering at Princeton University. Lin's research areas include Natural Hazards and Risk Analysis, Wind Engineering, Coastal Engineering, and Climate Change Impact and Adaptation. Her current primary focus is hurricane risk analysis, on which she has published in high-impact journals including *Science*, *Nature Climate Change*, and *Proceedings of the National Academy of Sciences*. Lin received her PhD in Civil and Environmental Engineering from Princeton University in 2010. Before rejoining Princeton as an assistant professor in 2012, she conducted research in the Department of Earth, Atmospheric and Planetary Sciences at MIT as a NOAA Climate and Global Change Postdoctoral Fellow.

CONTACT

(Prof) Ning Lin, Ph.D.
Assistant Professor
Princeton University
Dept. of Civil & Environmental Engineering
E-Quad E328
Princeton, NJ 08544,
USA

E: nlin@princeton.edu
T: + 1 609 258 0266
W: https://ninglin.princeton.edu/