A GLIMPSE OF TOMORROW

HOW THE CONSEQUENCES OF CLIMATE CHANGE ARE ALREADY EVIDENT AND HOW THEY CAN BE TACKLED

A compendium of essays for the
Allianz Climate Risk Research Award 2020

October 2020
Munich, Germany

Climate Risk
Research Award

Allianz �

ABOUT THE COMPENDIUM

The Allianz Climate Risk Research Award supports young scientists whose research improves our understanding of climate change-related risks. The 2020 Edition supports researchers whose work focuses on:

- Reducing the risk of extreme weather events that are intensified by climate change
- Fostering resilience by applying technological solutions

The compendium is a compilation of selected essays from participants of the 2020 Edition. This compendium is issued online only and is published exclusively for didactic purposes.

IMPORTANT INFORMATION

TABLE OF CONTENTS

LOCATIONS OF THE CONTRIBUTORS

What would Switzerland be without snow? The mountainous regions are dependent on winter tourism, and the snowpack is important for the water industry. Yet, the snow season is already far shorter than 30 years ago. The natural snowpack could shrink by up to 70% by 2100 and the ski season could start half a month or even a month later than it does today. By then, there will be only enough reliable snow cover for ski resorts to be profitable above 2500 m.

River floods are among the most damaging extreme climate events in Europe. Climate change is projected to increase the occurrence and frequency of once-in-a-century river floods in most regions , except for parts of northern Europe, southern Spain and Turkey. The direct damages could triple in the absence of additional adaptation measures. Pluvial floods and flash floods, triggered by intense local precipitation events, are likely to become more frequent.

Rising levels of greenhouse gases in the atmosphere create an imbalance in the energy flowing in and out of the planet. About 90% of that additional energy ends up stored in the oceans, which is warming the sea and fueling the intensity of cyclones. Tropical cyclones are expected to decrease in frequency but feature far more intense and long-lasting winds with increases in extreme waves and rainfalls.

The tropical and extratropical storms that ravage the Caribbean are becoming stronger, which increases their power of destruction. Other climate-related drivers of risk for small islands include sea level rise, increasing air and sea surface temperatures, and changing rainfall patterns. The Economist warns, "Unchecked, global warming could overwhelm the efforts of even the most far-sighted island governments to adapt to it. That may force people to leave."

Scientists are uncertain whether climate change will increase the number of hurricanes but there is more certainty that warmer ocean temperatures and higher sea levels will magnify their intensity and impacts. Stronger hurricanes will be far more costly in terms of damages and deaths without action to make coastal (and inland) areas far more resilient.

Lena I. Fuldauer
Nationality: German
Location: United Kingdom

Fabian Willibald
Nationality: German
Location: Switzerland

Parisa Hosseinzadehtalaei
Nationality: Iranian
Location: Belgium

Nivedita Sairam
Nationality: Indian
Location: Germany

Isil Ece Ozer
Nationality: Turkish
Location: Netherlands

Andrew Magee
Nationality: British
Location: Australia

Xioninng Wu
Nationality: Chinese
Location: United States

Gabriela G. Nobre
Nationality: Brazilian
Location: Netherlands

Nadia Bloemendaal
Nationality: Dutch
Location: Netherlands

Clare Stephens
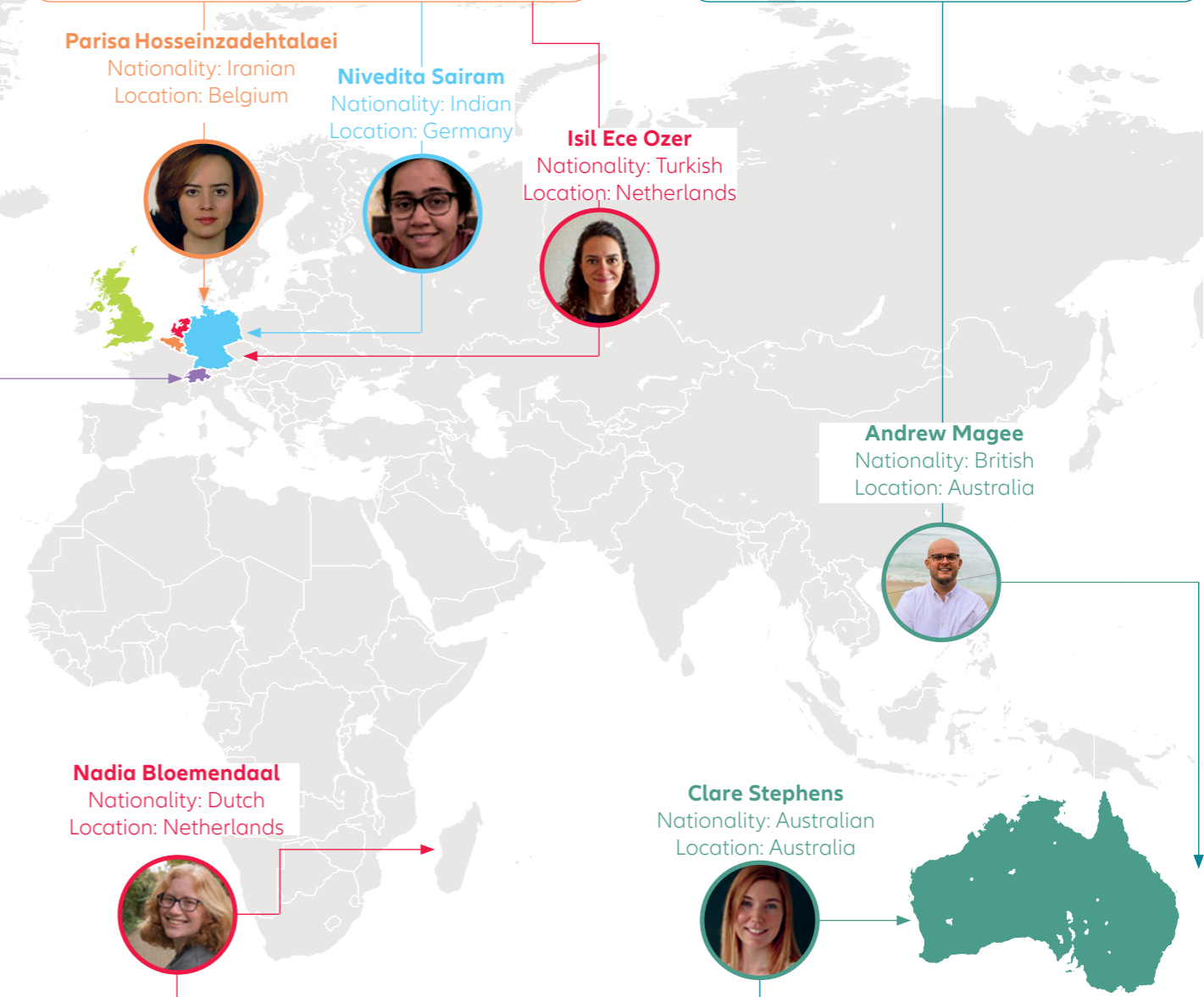Nationality: Australian
Location: Australia

El Niño and La Niña describe the warming and cooling phase of the El Niño Southern Oscillation (ENSO), a cyclical weather pattern in the central to eastern Pacific Ocean. Both are natural occurrences and can make extreme weather events more likely in certain regions, including droughts, floods and storms. Some scientists believe El Niño and La Niña may be becoming more intense and/or more frequent because of climate change.

Africa is expected to see more frequent and intense extreme weather events, such as droughts and heatwaves increasing the risk of desertification. Relatively little is known about hurricanes and Africa, but hurricanes are expected to have larger storm surges, to possibly decrease in frequency, while increasing in intensity and have increased rainfall. Scientists are working to improve their forecasts for hurricane and research on ocean and atmosphere interactions.

Australia has always been a land of extreme weather, but future generations will know ever more sunburnt, drought-stricken and flooded lands. The country is expected to get much hotter and its soil to degrade, unless damaging emissions are dramatically curtailed. Less rain is predicted but far more of it will fall when it does come. On land, more fires and heatwaves are expected; at sea higher surface temperatures and sea levels projected.

INTRODUCTION
THE WILL AND NOW THE MEANS

AMER AHMED
CEO, Allianz SE Reinsurance

Climate change is real, it is man-made, it is happening and regions and ecosystems around the globe are suffering devastating effects with a potential for dramatic social and economic disruptions.

Even if global warming were to magically stop today, Greenland's glaciers would continue to shrink. According to a _recent paper_ in _Nature Communications Earth and Environment_, Greenland's glaciers have receded so much that snowfalls that replenish the ice sheets cannot keep up with the ice flowing into the ocean.

Rising global temperatures have brought Greenland glaciers close to a tipping point, that is a threshold that once crossed will lead to unavoidable system break-down. Worse, they can create feedback loops that trigger a cascading set of other tipping points, in this case sea level rise.

Just over 10 years ago, Allianz, together with the WWF Global Climate Initiative, published a report on _Tipping Points_. The report explained how, if no action was taken, sea level rise on the East Coast of the United States, the shift to an arid climate in California, disturbances of the Indian Summer Monsoon in India and Nepal or the dieback of the Amazon rainforest due to increasing drought, are likely to affect hundreds of millions of people and cost hundreds of billions of dollars. Greenland's ice sheets and rising sea levels are listed there, too.

LEAD BY EXAMPLE

I am proud that Allianz was among the first companies to beat the drum on climate change and we matched words with action. Since 2005 we have become one of the world's largest financial investors in renewable energy. We have also been a carbon-neutral company since 2012. And we are leading the United Nations' convened Net-Zero Asset Owner Alliance to transition our investment portfolio to net-zero emissions by 2050 – this requires major changes in our traditional business model.

Also, we have teamed up with peers and public-sector partners to develop insurance solutions to enable climate-vulnerable societies to better deal with the impacts of climate change.

GREATER URGENCY

Yet, one cannot but be disappointed by the current inertia on climate action globally. When the _Tipping Points_ report was published, the threats were well-known, but expectations were that we would still have plenty of time to get climate change under control.

That assumption has been shattered. The United Nations' Intergovernmental Panel on Climate Change (IPCC) warned in October 2018 that we had only a decade left to prevent system collapses that could hasten the speed of global warming and limit the impact from reducing carbon emissions.

But it is the state of the Greenland glaciers that drives home the point most strongly. Is this a reason for despondency or despair? Absolutely not! It reinforces the need to tackle climate change head on with all our energy and all the determination we can muster. In this, I am cheered by the technical advances made in the past decade.

CARBON-ZERO FUTURE

We currently have the means to subdue over 80 percent of man-made emissions. And over the 2020s, this ability will become even better as low-carbon technologies are further developed and scaled.

Solar, wind and battery technologies are now as cheap or cheaper than fossil fuels at the industrial level and the gap is widening. The exponential trajectories of these "clean" energy sources, if sustained, will be enough to halve emissions from electricity generation by 2030.

Further, with the 'tipping point' for the purchase price of electronic vehicles (EVs) to be on par with internal combustion engines by 2022/2024, EV growth has the potential to reach, by some projections, a 51 percent market share by 2030 and 90 percent by 2040 in rich countries. Meanwhile, hydrogen fuel cells for new generations of long-haul trucks, ships and trains are expected this decade, with clean synthetic fuel for jets expected somewhat later.

Simply put, we can begin to ratchet up the technologies needed to avert the worst climate scenarios. And we can power this by smartening up the financing behind it. A $90 trillion alliance (Principles of Responsible Investment) of global investors (including Allianz Global Investors) and wealth funds is, for example, already operating on the assumption that the fossil-fuel economy will go the way of the horse-and-buggy. We have teamed up with peers and public-sector partners to develop insurance solutions to enable climate vulnerable societies to better deal with the impacts of climate change.

THE ROLE OF SCIENCE

Science is the bedrock of our ability to anticipate, reduce and manage risks from a changing climate. Without the efforts of young scientists such as those featured in this compendium, we would not be able to understand the interconnectedness and the sensitivity of tipping points, such as the survival of the Greenland glaciers, until it is far too late.

I thank all participants for submitting their entries for the award. And particularly for your dedication, your focus and your incredibly valuable efforts to secure our future.

> "
> We have teamed up with peers and public-sector partners to develop insurance solutions to enable climate vulnerable societies to better deal with the impacts of climate change.
> "

FOREWORD
ARE CLIMATE RISKS INSURABLE?

The COVID-19 pandemic that has been spreading since early 2020 appears to dwarf any other challenge the world has faced in the last decades. Most notably, this crisis is attracting public attention at historically unprecedented levels: Experts estimate that up to 85% of all publications that appeared this spring – ranging from scientific articles over yellow-press pieces to social-media entries – were dedicated to the coronavirus crisis. Yet below the public-perception surface, *the other crisis*, namely anthropogenic global warming (AGW), creeps on, manifesting itself in all sorts of devastations.

While I write these lines, wildfires are raging across the world-famous vineyards of California and the largest wetland on Earth, the Brazilian Pantanal. Floods and locust invasions plague huge parts of Northeast Africa. Heat waves travel across Asia. Tremendous volumes of "eternal ice" are melting in the Arctic and even in Antarctica. And tropical storms keep forming in the Caribbean at a record frequency. Most of these events and developments can be – directly or indirectly – attributed to man-made climate change as driven by the burning of fossil fuels. As a consequence, global mean surface temperature has already risen beyond pre-industrial levels by almost 1.2°C, which is quite a margin in light of the Paris Agreement that aims to limit AGW to "well below 2°C."

PROF. HANS JOACHIM SCHELLNHUBER
Potsdam Institute for Climate Impact Research (PIK)

THE 2°C QUESTION

Why 2°C? The ultimate answer will be given below. Let us first look at present and projected negative climate impacts through the lens of the insurers. Risk is usually quantified as the monetary damage caused by an event multiplied with the event's probability, although insurers tend to define risk more precisely as the annualized (assuming the probabilities are expressed on a per annum basis) expected losses of an event.

In any case, both definitions imply that statistics are of fundamental importance for insurance. But statistics best work if the probability distributions are derived from large *ensembles* of the event type in question (earthquake, hurricane, drought, car accident, etc.) and are *stationary* for the given constituency. In other words, the likelihoods can be looked up in empirical tables that date back to the Romans – at least.

Unfortunately, AGW is going to kill much of this evidence base, so the calculation of appropriate premiums will become more challenging, if not impossible, in certain instances. Let us start with the stationarity assumption, which will be undermined in two major ways. Firstly, regimes of deleterious events shift in geographical and/or parameter space. For instance, specific regional wind fields and precipitation patterns may move northward with increasing global warming – possibly toward locations where people are not adapted to them. Or the phenomena stay put, yet, become more powerful and dangerous. That will most likely happen in the sub-tropical Atlantic, where high-category (4, 5 or even the new grade 6) hurricanes may emerge quite a few times every storm season.

Secondly, entire large-scale entities of the familiar planetary environment may be transformed or even extinguished by climate change. These are the so-called *tipping elements* (atmospheric and marine circulation patterns, ice sheets, quintessential ecosystems, etc.), which can change in character disruptively at certain levels of warming. Beyond the respective tipping points, traditional wisdom evaporates, and conventional insurance schemes fail. If the Indian summer monsoon becomes more volatile or even chaotic, how should one set up an affordable risk sharing system? Before I comment on this mind-boggling challenge, let me quickly answer the 2°C-question raised above: There is compelling scientific evidence (see, e.g., Schellnhuber et al. 2016, *Nature Climate Change*) that most tipping elements will be unsettled if global warming overshoots the Paris corridor!

A WORLD WITH NO PRECEDENTS

Note that not only the stationarity principle but also the ensembles approach will be dead in that case: The relevant events are singular in character, happening only once in a geological era and thus defying any human experience. There is no manual how to manage the shutdown of the Gulf Stream.

> " The highest priority is to reduce rather than increase uncertainty. This implies nothing less than to completely decarbonize the global economy by 2050 (or, even better, by 2040.) "

What can societies do in this state of utter confusion? Well, the highest priority is to reduce rather than increase uncertainty. This implies nothing less than to completely decarbonize the global economy by 2050 (or, even better, by 2040). Insurance companies in their role as top investors and with their know-how on building resilience to weather extremes should help to achieve this.

When it comes to the core business of insurance, novel schemes need to be developed, considering multiple timelines that range from years to decades and even centuries. This can only be achieved through public-private partnerships without precedence. Innovative insurance is particularly necessary in the Global South, where poor capacities meet high vulnerabilities.

JOSIAS RITTER
Winner of 2018 Award

"I believe that the work young researchers undertake has absolute relevance for our world. The Allianz award is a refreshing acknowledgement reminding us that all the hours and efforts we spend in research are appreciated. It motivates people like me to keep pushing forward towards a better future."

SPATIALLY ASSESSING HAZARD IMPACTS

AUTHOR
Lena I. Fuldauer

INSTITUTION
University of Oxford, Environmental Change Institute, UK

BIOGRAPHY
Lena Fuldauer is a doctoral researcher at the Environmental Change Institute at the University of Oxford. She has developed and applied national systems models, which have been successfully used for assessing risk of extreme hazards and impacts on development worldwide, including studies in Curacao, Saint Lucia and currently in Ghana. Lena has organised various capacity development workshops to train stakeholders from ministries, private sector and academia on the use of systems modelling tools to inform adaptation planning to deliver on global goals.

TITLE OF THESIS
Climate change hazard impacts on sustainable development, and national adaptation responses

CONTACT
lena.fuldauer[at]eci.ox.ac.uk

New methods are required to understand the impacts of extreme hazards posed by climate change to both our built and natural environments. A proposed systems approach provides spatial insights into the impacts of hazards across interdependent assets and all dimensions of sustainable development to help national decision-makers and insurance companies better prioritize adaptation and devise insurance premiums.

The risk of extreme hazards, such as floods or storm surges, will increase with climate change and affect built and natural environment assets critical for national development and achievement of the United Nations' 17 Sustainable Development Goals (SDGs). Recent advances have catalysed an understanding of climate change hazard impacts at a high spatial granularity by overlaying hazard and asset information. These advances have traditionally focused on assessing impacts of hazards on individual assets (for example, energy assets) with high economic value. However, without considering a holistic set of both built and natural environment assets and interdependencies, it is not possible to target adaptation to foster societal resilience for sustainable development.

My research develops a novel systems approach that for the first time spatially assesses impacts of hazards across a nation's entire built and natural assets – including energy, health care or ecosystems – and the ways in which impacts may interact to influence the SDGs (Figure 1).This provides national decision-makers and insurance companies with evidence and tools to prioritize climate adaptation and devise insurance premiums that reduce hazard impacts and foster societal resilience.
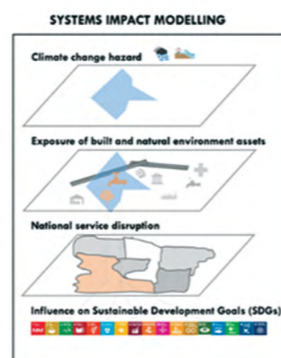
**Figure 1:** Systems impact modelling, applied in Saint Lucia.

INFORMING STATEGIC ADAPTATION IN SAINT LUCIA

My research found practical applicability in a recent climate adaptation assessment in the Caribbean island of Saint Lucia. Working in close collaboration with the Saint Lucia Ministry of Finance, I standardized data across the built and natural environment assets of the island to model hazard impacts. Further, I conducted multiple workshops with government officials and academics to ensure the required capacity to iteratively update data and utilize the modelling (Figure 2).
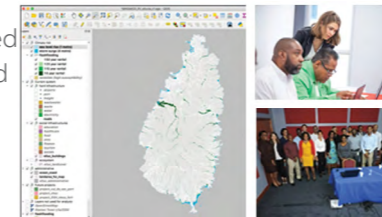
Figure 2: Saint Lucia's capacity building workshop on the modelling tool, see here for a summary video.

In 2018, Saint Lucia proposed a national adaptation plan to reduce impacts of future hazards, aligned with commitments under the Paris Agreement. Application of my systems impact modelling provided the evidence, at high spatial granularity, of the areas or assets to prioritize in implementing this national plan. For example, the modelling indicated that cumulatively, Saint Lucia's built environment assets in the north-west are mainly exposed to both storm surges and landslides, while the island's natural environment assets in the south-west are particularly exposed to landslides (Figure 3a).
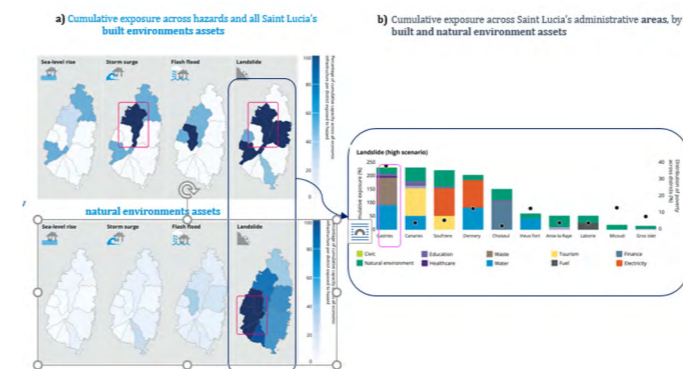
Figure 3: a) Saint Lucia's built and natural environment assets exposed to hazards in different areas; b) prioritisation of areas based on cumulative asset exposure following a landslide as well as the distribution of poverty.

More specifically, my research identified that a landslide in the Castries area in Saint Lucia's north-west can disrupt more than 85% of the area's water and waste management capacity and 20% of the natural environments. Further, Castries is characterized by a large poverty distribution, which makes its population vulnerable to hazards (Figure 3b). Prioritizing adaptation in Castries, for example through hazard-proof designs or

insurance solutions, can safeguard the provision of critical water and waste management services for at least 4,000 households and conserve ecosystem services, fostering societal resilience amongst this vulnerable population.

Beyond single hazards and individual assets, a key aspect of my research includes considering multiple hazards and asset interdependencies. One research finding is that a combined storm surge and flash flood hazard, common in Saint Lucia, can expose the wetland in the island's north-west (Figure 4). This exposure can disrupt the natural flood protection services the wetland provides for the surrounding built environment. Before my research, decision-makers in Saint Lucia considered removing this wetland in favour of new developments.
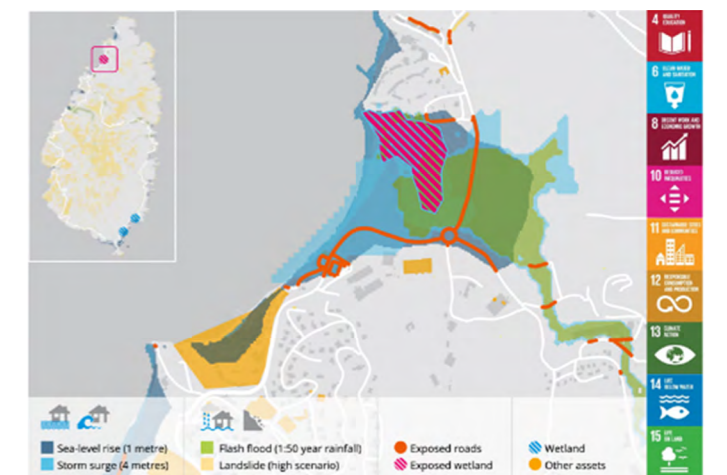
Figure 4: Saint Lucia's wetland exposure has independent impacts on the nearby critical road network, influencing nine SDGs.

My modelling showed that conserving this wetland protects the only north-south road, which provides access to 27,000 vehicles daily. These vehicles transport people to educational and work places, and move critical cargo, including water and food. Beyond ecosystem benefits, conserving this wetland can influence eight dimensions of sustainable development, including education (SDG4), decent work (SDG8), and clean water (SDG6).

EVIDENCE-BASED INVESTMENTS

The proposed systems approach provides new spatial insights into the impacts of hazards across interdependent assets and all dimensions of sustainable development. The systems approach can be repeated with hazard maps representing changing risk with climate change and transferred to other climate-vulnerable nations. Application of systems impact modelling helps national decision-makers and insurance companies better prioritize adaptation and devise insurance premiums. Aligning investments with the SDGs and the Paris Agreement contributes to build the much-needed climate resilience for a sustainable future.

FLOODS OF PROBLEMS
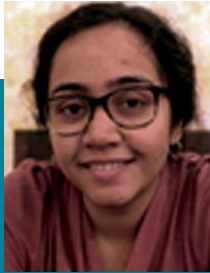
AUTHOR
Nivedita Sairam

INSTITUTION
German Research Centre for Geosciences, Potsdam, Germany

BIOGRAPHY
Nivedita is a Ph.D. researcher in the Hydrology Section of the German Research Centre for Geosciences (GFZ), Potsdam, Germany. Her current research focuses on conceptualizing, developing and testing novel statistical approaches for improving flood loss prediction across Europe. After her Ph.D. (from December 2020), she will continue to work a Post-Doc researcher at the same institute during which she will adapt her research to countries in South-East Asia.

TITLE OF THESIS
Reliable, flexible and accessible flood loss prediction models using Bayesian approaches

CONTACT
nivedita[at]gfz-potsdam.de

Despite recent advancements, flood loss models show a lack of reliability, flexibility and accessibility. To support risk-based adaptation measures and insurance pricing, we need reliable, flexible and accessible flood loss prediction models.

Owing to changing climate and rapid urbanization, extreme flood events are increasingly common. The European Environmental Agency estimated that during 2010-19, the EEA (European Economic Area) countries suffered a cumulative €13 billion a year due to extreme weather events. The misery of recent floods in the states of Assam and Kerala in India, and the Myagdi district in Nepal has compounded the devastation caused by the current COVID-19 crisis.

The role of insurance in flood risk management is indispensable. Insurance can drive planning and resilience strategies in addition to risk transfer. For example, incentivizing property-level adaptation via premium discounts promotes insurance penetration and enhances flood resilience.

Risk-based pricing and parametric insurance solutions can create a paradigm shift in flood risk insurance products. A step in this direction is my doctoral research on development and implementation of probabilistic flood loss models.

These models support risk-based insurance pricing and adaptation decisions by enhancing the vast compendium of state-of-the-art flood loss models using empirical and expert knowledge from diverse case studies. Providing access to these models through the OASIS Loss Modelling Framework (LMF) is in progress.

BACKGROUND

The evolution of flood loss models began from simple stage-damage equations where loss is predicted based on water depth. Enhanced computation capabilities and machine learning algorithms have led to the development of sophisticated models using predictors that include flood duration, contamination (oil or sewage), dwelling characteristics and adaptation measures.

Despite these advancements, flood loss models show a lack of reliability, flexibility and accessibility. My research under the SystemRisk EU2020 project (2016-2020) focused on advancing loss models to overcome these limitations and bridging the gap between research and practice.

ROLE OF PROPERTY-LEVEL ADAPTATION

Households situated in flood-prone areas are often encouraged to implement property-level adaptation measures. The adaptation policies are commonly based on expert judgment and/or non-transparent datasets. My first study is a methodological framework using an open-source empirical database from Germany, HOWAS21 to estimate the loss-reducing effect of adaptation measures. We established that property-level adaptation measures reduce losses by 27% (€12,000-15,000), per household (Sairam, N., Schröter, K., Lüdtke, S., Merz, B., & Kreibich, H. (2019). "Quantifying flood vulnerability reduction via private precaution." *Earth's Future*, 7, 235– 249).

Integrating this adaptation effect within loss models paves the way to incentivize property-level measures via premium discounts. This is, however, only possible when loss models are able to predict with superior accuracy and low uncertainty. Therefore, the rest of my research focused on enhancing loss predictions via better models and analyzing comprehensive case studies.

ENHANCING RELIABILITY

Flood loss predictions are uncertain and lack reliability. Uncertainty does not imply ignorance. However, the lack of approaches to explicitly quantify the loss prediction uncertainty impedes risk-based adaptation and insurance solutions.

One of the first efforts to quantify uncertainty in loss predictions was my contribution to the development of a probabilistic beta regression model – BR-FLEMO (Rözer, V., Kreibich, H., Schröter, K., Müller, M., Sairam, N., Doss-Gollin, J., et al. (2019). "Probabilistic models significantly reduce uncertainty in Hurricane Harvey pluvial flood loss estimates." *Earth's Future*, 7, 384– 394).

In comparison with state-of-the-art models, BR-FLEMO improved prediction reliability of losses due to the Hurricane Harvey by 78% ($3.8 billion). Households can qualify for risk-based pricing by applying thresholds on prediction reliability. Since the performance of BR-FLEMO depended on data availability from past events, my next study was on adapting BR-FLEMO to data-scarce regions.

BUILDING FLEXIBILITY

Lately, flooding has affected regions that were previously considered "low risk" (for example, behind dykes). These regions may have no recorded flood event or relevant loss model from the recent past. Flood loss models are often erroneously used from other regions for developing risk portfolios for these regions. Loss models are always sensitive to changes in region and event characteristics. Within Germany, this lack of flexibility across regions increased prediction errors by 20% (Sairam, N., Schröter, K., Rözer, V., Merz, B., & Kreibich, H. (2019). "Hierarchical Bayesian approach for modeling spatiotemporal variability in flood damage processes." *Water Resources Research*, 55, 8223– 8237).

My approach to build flexible loss models was done in two steps. First, the highly reliable BR-FLEMO was extended to a multi-level structure to establish compatibility across six events from four regions in Germany based on the HOWAS21 database. The multi-level structure enhanced model flexibility and reduced the prediction errors by 50%.

Second, to expand this model to Western Europe, I leveraged the hydrology and social science expertise of SystemRisk consortium partners from Germany, Italy, Netherlands and the UK. Integrating BR-FLEMO with expert and empirical knowledge from these countries provided reliable loss prediction for potential future flood events in Europe (Sairam, N., Schröter, K., Carisi, F., Wagenaar, D., Domeneghetti, A., Molinari, D., ... & Kreibich, H. (2020). "Bayesian Data-Driven approach enhances synthetic flood loss models." *Environmental Modelling & Software*, 104798).

PROVIDING ACCESSIBILITY

The development and implementation of BR-FLEMO was supported by continuous feedback from the insurance industry. To improve usability and help decision making under uncertainty, BR-FLEMO follows the principle of parsimony concerning input data requirements and is rigorously validated against empirical data.

The methodology and validation of BR-FLEMO are published in peer-reviewed journals. BR-FLEMO can be trained with new data and extended geographically. This promotes transfer of knowledge from established case studies to flood-prone regions that lack adequate monitoring systems and data acquisition standards. To improve model accessibility, we are currently working on the model standardization according to the OASIS LMF specifications.

THE PERFECT STORM

AUTHOR

Nadia Bloemendaal

INSTITUTION

Vrije Universiteit Amsterdam, Netherlands

BIOGRAPHY

Nadia is a final year climate risk Ph.D. candidate at the Vrije Universiteit Amsterdam, the Netherlands. She has a BSc in Applied Mathematics from the University of Twente and a MSc in Meteorology, Physical Oceanography and Climate from the University of Utrecht, both in the Netherlands. Her current research focusses on improving the understanding of global tropical cyclone risk. The ultimate goal is to provide a detailed risk portfolio for any coastal region in the world.

TITLE OF THESIS

Tropical cyclone risk under climate change

CONTACT

nadia.bloemendaal[at]vu.nl

Performing risk analysis on tropical cyclones can be difficult because of the lack of historic data for many regions. A creative data-driven approach known as STORM has created a global dataset on tropical cyclone risk stretching over 10,000 years.

When Cyclone Idai made landfall in March 2019, it tore a destructive line straight through southern Africa devastating Mozambique, Zimbabwe and Malawi as it passed. More than 1,300 people were killed with many more missing after high winds, torrential rain and flooding lashed the three countries.

Idai proved to be the deadliest tropical cyclone ever recorded in the South-West Indian Ocean basin, a zone south of the equator and west of 90° E of the coast of Africa where many Southern Hemisphere cyclones are birthed.

Although towns and villages were completely ravaged and many people lost their lives, the most memorable image was of a pregnant woman who gave birth to her daughter while clinging for dear life to the branches of a mango tree in Mozambique. It was a small tale of resistance and hope amongst all the destruction.

Tropical cyclones such as Idai, also often referred to as hurricanes or typhoons, are amongst the deadliest and by far the costliest of natural disasters. They make regular landfall on almost every continent, affecting people, economies and the environment through their high wind speeds, heavy rains and storm surges.

Over the last decade, the world has witnessed numerous devastating tropical cyclone events. The 2017 Atlantic Hurricane season became the costliest ever with six major hurricanes, including Harvey, Irma and Maria, combining to cause losses of $294.92 billion and at least 3,364 deaths.

In 2019, Cyclones Idai and Kenneth caused widespread havoc in southeast Africa, while Hurricane Dorian became the strongest to ever hit the Bahamas, with sustained wind speeds exceeding 295 km/h (183 mph).

INCREASING FURY

Evidence is emerging that the unnatural effects of human-caused global warming are already making hurricanes stronger and more destructive in nature. With tropical cyclones already significantly affecting communities under present-climate conditions, climate change is adding to the risk from two sides.

First, it is projected that cyclones will become even more intense, with an expected increase in maximum wind speeds, storm surge heights and precipitation. Further, with populations growing in many coastal areas, more people and assets will be exposed to severe cyclones. Minimizing loss of life and property requires risk reduction efforts supported by accurate risk assessments.

Performing such risk assessments can, however, be challenging when historical data only. This is because tropical cyclones are relatively rare, with around 90 formations per year, and only a fraction making landfall. Additionally, when cyclones make landfall, they only affect a relatively small stretch of coastline (<500 km). Finally, reliable tropical cyclone datasets are only available from 1980 onwards, which means many coastal regions may not have even a single landfall event recorded in the data.

The result is that many regions lack information about potential magnitudes and probabilities, particularly for extreme events. This complicates reliable tropical cyclone risk assessments and risk management.

WEATHERING THE STORM

To address the limitations of existing datasets, a methodology of generating synthetic tropical cyclones was developed. In this approach, cyclone tracks are taken from a meteorological dataset and are statistically resampled and modelled to generate synthetic but realistic tropical cyclones.

This procedure is repeated recurrently to create a tropical cyclone dataset that has the same statistical characteristics as the original dataset, but spans hundreds to thousands of years. Using this approach, the novel Synthetic Tropical cyclOne geneRation Model (STORM) was developed, which has been published in *Scientific Data, a journal from Nature*.

The STORM dataset is equivalent to 10,000 years of tropical cyclone activity under present-climate conditions. Therefore, the dataset is unique and enables statistical analysis of probabilities of various tropical cyclone events globally.

To demonstrate its usage, the 10,000 years of tropical cyclone tracks were combined with a 2D-parametric wind field model to calculate wind speed probabilities at a resolution of 10 km (6.2 mi) globally (Bloemendaal et al., in review). This study is the first of its kind to provide a wealth of information on such probabilities globally, including for islands such as the Small Island Developing States and regions that are not frequently hit by tropical cyclones.

The data is particularly useful for local governments, stakeholders and insurance companies as this study delivers detailed information on extreme (low probability) events that might not have yet been observed.

TEMPESTUOUS WINDS

AUTHOR
Andrew Magee

INSTITUTION
University of Newcastle, Australia

BIOGRAPHY

Dr Andrew Magee is a Postdoctoral Researcher at the Centre for Water, Climate and Land (CWCL), University of Newcastle, Australia. Better understanding the relationship between climate variability and tropical cyclone behaviour is at the nexus of Andrew's research interests. He has published widely on the link between ocean-atmosphere interactions and implications on tropical cyclone behaviour. Andrew works closely with researchers, governments, insurers, financial institutions and aid organisations across Asia-Pacific on projects focusing on tropical cyclone risk, natural peril and hazard risk modelling, stochastic weather generation and seasonal tropical cyclone forecasting.

TITLE OF THESIS

Tempestuous winds and vulnerable island nations: a new tropical cyclone outlook for the Southwest Pacific

CONTACT

andrew.magee[at]newcastle.edu.au

A new generation of long-range tropical cyclone outlooks for the Southwest Pacific provides, for the first time, tailored guidance for 12 vulnerable island and regional-scale locations. These offer unprecedented lead times of up to four months before the official start of the cyclone season and consider the most recent changes in ocean-atmosphere variability providing a substantial advantage for people, governments, aid agencies and other end-users to prepare.

Tropical cyclone Winston, a record-breaking category-five storm, was the strongest and costliest cyclone to ever make landfall across Fiji. Striking the island nation in 2016, Winston killed 44 people, injured a further 130 and caused catastrophic damage ($1.4 billion) across Fiji and beyond.

Tropical cyclones produce extreme winds, large waves, storm surges, intense rainfall and flooding. On average, 11 tropical cyclones form in the Southwest Pacific each season and account for almost three in four natural disasters across the region. Since 1950, tropical cyclones have claimed almost 1500 lives, displaced an additional 3 million people and caused losses of more than $9 billion.

The vulnerability of Pacific Island nations and territories to tropical cyclone impacts is amplified by their geography and economies. Their geographical remoteness complicates the humanitarian aid response in the aftermath of a cyclone, while developing economies feature slow economic growth and fragile infrastructure that hampers their abilities to prepare against and rebound from tropical cyclones. As a result, when an event like Winston occurs, it wreaks havoc and devastation upon communities, lives and economies across the region and the effects can ripple down for years.

CHALLENGING THE STATUS QUO

Current generation tropical cyclone outlooks provide regional guidance every October for the Southwest Pacific Tropical Cyclone season, which runs from November to April. These model the expected number of tropical cyclones and afford end-users a few weeks' notice to prepare before the official start of the season.

However, current efforts to produce outlooks only consider how the El Niño-Southern Oscillation (ENSO) might influence where and when tropical cyclones may form across the basin. Recent research has shown that ENSO is not the only climate influence on tropical cyclone activity in the region.

Different flavours of ENSO, interdecadal climate variability (Magee, A. D., Verdon-Kidd, D. C., Diamond, H. J., & Kiem, A. S. (2017). "Influence of ENSO, ENSO Modoki and the IPO on tropical cyclogenesis: a spatial analysis of the southwest Pacific region." International Journal of Climatology, 37(S1), 1118–1137) and sea surface temperature variability in the Indian Ocean (Magee, A. D., & Verdon-Kidd, D. C. (2018). "On the relationship between Indian Ocean sea surface temperature variability and tropical cyclogenesis in the southwest Pacific." International Journal of Climatology, 38(January), e774–e795) can significantly influence tropical cyclone behaviour.

In a world-first, the Long-Range Tropical Cyclone Outlook for the Southwest Pacific (TCO-SP) now provides tailored tropical cyclone outlooks for 12 island and regional-scale locations (see Figure 1). TCO-SP produces skillful outlooks in July, offering unprecedented lead times of up to four months before the official start of the season (Magee, A. D., Lorrey, A. M., Kiem, A. S., & Colyvas, K. (2020). A new island-scale tropical cyclone outlook for southwest Pacific nations and territories. *Scientific Reports*).

TCO-SP offers rolling monthly outlook updates between July and January, which considers the most recent changes in ocean-atmosphere variability to produce pre- and in-season outlooks. This offers a substantial advantage for end-users to prepare in the months leading up to a season.

Figure 1: TCO-SP outlook regions. Black labels indicate individual island-scale outlooks. White labels indicate sub-regional outlooks.

LOOKING BACK TO LOOK FORWARD

TCO-SP guidance is trained on historical tropical cyclone seasons (from 1970 onwards) and uses sophisticated algorithms to determine the optimum combination of ocean-atmosphere predictors. This technique tests thousands of potential predictor model combinations, before selecting the most skillful combination. Doing so for each monthly update, and for each location, produces a bespoke outlook model based on historical tropical cyclone variability.

The skill of TCO-SP models is unmatched. Outlooks generated in July for New Caledonia (four months before the start of the season) have a strike rate of 34% (that is, correctly predicted tropical cyclone counts for 17 seasons out of 50 between 1970 and 2019) and a strike rate (±1 TC) of 84%, that is for 42 seasons out of 50 (See Magee et al., (2020) for more information).

REDUCING DISASTER RISK

TCO-SP outlooks are freely available at www.tcoutlook. com. Deterministic (tropical cyclone counts) and probabilistic (likelihood) guidance is provided for 12 locations across the region and designed to meet the needs of a range of end-users. Detailed guidance is available for local meteorological and hydrological services, disaster managers, governments, aid agencies, insurers and financial institutions, business owners and many others who want to evaluate their risks for the coming season. A summary and interactive map of the guidance is also available for those who only require a snapshot of the coming season, such as the public.

The methodology of deriving TCO-SP outlooks can be applied, updated and retrained to incorporate tropical cyclone counts from the most recent seasons. As such, with the sample size constantly increasing, we expect future improvements for model skill and a reduction of uncertainty for island-scale outlooks using this approach. The continuous retraining of TCO-SP means that emerging trends driven by anthropogenic climate change are considered when seasonal guidance is produced, future-proofing TCO-SP for many years to come.

Rising sea levels and changes to tropical cyclone related exposure and vulnerability will amplify future impacts across Southwest Pacific island nations and territories. Realistic island-scale guidance with unprecedented lead times offers many the potential to prepare in the months preceding the start of the season.

TCO-SP has the potential to save lives, reduce damage, financial loss and disaster risk, and assist with more effective humanitarian aid responses in the aftermath of a tropical cyclone. TCO-SP will play an important role in building a more resilient future for Pacific Island communities.

In addition to TCO-SP, the Long-Range Tropical Cyclone Outlook for Australia (TCO-AU) has recently been published (Magee, A. D. and Kiem, A. S. (2020). "Using indicators of ENSO, IOD and SAM to improve lead time and accuracy of tropical cyclone outlooks for Australia." *Journal of Applied Meteorology and Climatology*).

FLOOD PROTECTION FROM SPACE

AUTHOR
Işıl Ece Özer

INSTITUTION
Delft University of Technology, Netherlands

BIOGRAPHY
After completing her Ph.D. at Delft University of Technology, the Netherlands, Ece currently works at the same university as a postdoctoral researcher. Her research focuses on exploring how satellite technology can be applied in early warning systems of flood defences. The goal of her work is to mitigate the potential impact of floods by means of novel techniques to be used in flood risk management.

TITLE OF THESIS
Understanding Levee Failures from Historical and Satellite Observations

CONTACT
i.e.ozer[at]tudelft.nl

Satellite monitoring technology will play a crucial role in improving the safety of flood defences, which are essential in preventing catastrophic flooding events.

A week of continuous heavy rains that lashed Europe in August 2002, eventually caused swollen rivers to overflow their courses killing more than 100 people. Thousands were dispossessed and damage in €15 billion (of which only 15% was insured) was recorded across nine countries.

The floods, which reached unprecedented heights, were of a magnitude expected to occur roughly every hundred years. One factor that made the floods so devastating was that levee failures occurred at locations considered safe according to conventional levee assessments.

Such earthen levees form a significant part of the existing flood defences in safeguarding the land against catastrophic flooding events. Despite the critical function of levees in flood safety, conventional inspection methods mostly rely on limited information acquired by expert observers in the field, resulting in infrequent, qualitative and subjective assessments of their status. In many cases, periodical inspections meant to assess the levee conditions have not been able to foresee failures, such as during the 2002 Elbe flooding.

Given that remote sensing and in-situ techniques are mostly expensive and/or time-consuming, they are used to a limited extent, often locally and for a short period of time. Besides, little is known of what determines the structural behaviour of levees in time and what are the underlying causes of their failures.

This hampers the timely detection of weak spots and the assessment of levee safety in general. Being able to identify if, where and when a levee failure would suddenly occur is an important aspect of levee safety management.

MEASURING ON A MILLIMETRE-LEVEL FROM KILOMETRES AWAY

This research shows satellite technology, in particular satellite radar interferometry (InSAR), is an innovative and cost-effective tool to present detailed information about the deformation behaviour of levees. It provides millions of observations on a time scale of days, with millimetre-level precision, during the day and at night, anywhere on the planet.

Using satellite technology for levee safety is most beneficial when applied to the detection of potential problematic locations in a timely manner. Such an early warning system requires two main aspects to be taken into consideration. These are namely (a) understanding the deformation behaviour of a levee under varying loading conditions (explainable deformation) and (b) finding the deviations from this normal behaviour (anomalies), which may be early indicators of a potential failure.

"BREATHING" OF THE LEVEES

When looking at a levee during an expert inspection, no one would be able to detect any motion in this robust structure. In fact, levees swell and shrink on a millimetre-level as a response to loading conditions, such as changing water levels, precipitation and temperature. By observing this "breathing" of levees, satellites provide us with important information regarding their behaviour and stability.

In this research, this feature is used to create an innovative deformation model based on satellite and meteorological data to understand and describe the dynamics of the levee behaviour in greater detail. The model allows the authorities to better analyse the effects of different loading conditions on the swelling and shrinking behaviour of levees on a weekly basis.

Until now, this behaviour has never been observed at this temporal and spatial scale. By determining whether the deformation observed by satellites is in line with the predicted levee response, it would become possible to identify problematic locations and apply the appropriate countermeasures.

EARLY WARNING SYSTEMS

For this purpose, the research focuses on developing a prototype early warning method using a probabilistic approach to detect and analyse anomalies along the levees. The method aims to evaluate whether a levee follows its expected behaviour or deviates significantly from it.

The proposed approach intends to advance the applicability of the technique as a diagnostic tool for levee safety assessments. The presence of anomalies in the observed deformation can be an indication of potential problematic locations which should be further investigated by the authorities. Such an automated system allows the levee behaviour over extensive areas to be readily assessed, with alerts raised only when significant, localized and concurrent anomalies are detected.

Climate projections commonly agree that the future will bring more extreme conditions, such as storms, high river discharges or droughts. In this respect, a systematic application of the developed method can contribute to reducing uncertainties in levee behaviour and detecting locations most prone to sudden failures. This will assist the responsible authorities in flood management to take appropriate actions, hence enhancing flood protection and reducing flood risk.

When the expected economic and demographic growth of the future are considered, the safety of flood defences becomes of even greater importance in managing flood risk. The protection capacity of these structures against future conditions highly relies on their continuous monitoring, maintenance and design improvements.

FROM EARLY WARNING TO EARLY ACTION

AUTHOR
Gabriela Guimarães Nobre

INSTITUTION
Vrije Universiteit Amsterdam, Netherlands

BIOGRAPHY
Gabriela obtained her Ph.D. in Early Warning Early Action at Vrije Universiteit Amsterdam (Netherlands) in 2019, where she currently works as a Postdoctoral Researcher at the Institute for Environmental Studies. She is also a consultant at the Research, Assessment and Monitoring Division at the United Nations World Food Programme. In both institutions, her research focuses on the use of forecasting models for achieving disaster risk reduction. Gabriela has published several scientific papers in this field.

TITLE OF THESIS
Floods, droughts and climate variability: from early warning to early action

CONTACT
g.guimaraesnobre[at]vu.nl

As measurements move from disaster management to pre-empting the risks through early action, accurate forecasting information will be critical to steer risk reduction measures.

In January 2017, the Famine Early Warning System Network, an American-funded organization that monitors some 30 countries, forecasted an unprecedented food security crisis, requiring emergency food assistance to more than 70 million people. In some African countries food insecurity was primarily driven by an ongoing severe drought.

Despite the warning, across 45 countries, millions felt into a deep humanitarian crisis. In Somalia alone, some 16 million people were left on the brink of starvation, more than 1 million displaced and damages were estimated at over $3 billion.

Food insecurity is a global recurrent crisis, and droughts and floods important drivers. These hazards have high socio-economic impacts, such as crop failures and the widespread death of livestock. Malnutrition levels also surge on such occasions.

The chain of impacts often begins when rainfall is significantly lower or higher than average. Therefore, floods, droughts and food insecurity have strong links with climate variability, such as the El Niño-Southern Oscillation (ENSO).

ENSO is an irregularly periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean. It is the main driver of year-to-year fluctuations in global weather and climate patterns, posing a serious impact on rainfall regimes across the African continent.

IMPACT BASED FORECASTING

Currently, disaster risk reduction (DRR) requires a substantial shift from managing disasters to managing risks. An important step to achieve DRR lies in understanding how climate variability results in flood and drought. The impact of disasters can then be reduced when forecast information is available to steer risk reduction measures.

These systems have improved rapidly in recent years, and predictions of flood and drought hazards can be made with higher accuracy and with longer lead times than ever before. However, there is still a gap in translating hazard information into impact information, such as damage from weather events. Hence, an important research challenge is the transition from "what will the weather be?" to "what will the weather do?".

Forecast information that expresses potential impact is known as "impact-based forecasting." When an impact-based forecasting system is available, early actions can be automatically triggered to reduce the impacts of weather events.

ENABLING THE SHIFT FROM DISASTER TO RISK MANAGEMENT

Our capability to prepare for disasters is challenged by large uncertainties and our limited understanding of important driving forces behind hydro-meteorological hazards, such as climate variability. To act on forecasts, it is important to understand the potential impacts associated with such events.

The main objective of my research is exactly this, to improve the understanding of links between climate variability and weather-related impacts of both floods and droughts. I investigate this relationship from global to regional scales, and at different lead times, with the purpose of achieving an impact-based forecast that could guide the implementation of early actions effectively before a potential drought or flood materializes.

FROM CLIMATE VARIABILITY TO IMPACTS

Scientific evidence on the relationship between climate variability and the socioeconomic impacts of floods and droughts is still limited. Therefore, using a pan-European scale assessment, I investigated links between large-scale climate variability and the occurrence and intensity of extreme rainfall, as well as anomalies in flood occurrence and damage.

I found strong links between climate variability and extreme rainfall. For instance, anomalies in the occurrence and intensity of extreme rainfall linked to the positive/negative phases of the investigated indices of climate variability can be up to ±100% and ±60%, respectively. Furthermore, I have shown for the first time that flood damage and occurrence are strongly associated with climate variability, especially in southern and eastern Europe (Guimarães Nobre, Gabriela, et al. "The role of climate variability in extreme floods in Europe." *Environmental Research Letters*, 2017).

FROM EARLY WARNING TO EARLY ACTION

Impact-based forecasting information can improve the management of flood and agricultural risks. For instance, I have shown that flood losses can be predicted one season ahead because a lagged relationship may exist between indices of climate variability and flood losses in Europe (Guimarães Nobre, Gabriela, et al. "What will the weather do? Forecasting flood losses based on oscillation indices." *Earth's Future*, 2020).

Furthermore, I have shown that climate variability can be used to forecast anomalies in agricultural production. For example, sugar beet production could be predicted in 77% of the investigated regions, corresponding to 81% of total European sugar beet production. For nearly half of these regions, such impact-based information is available five to six months ahead of the sugar beet harvesting season (Guimarães Nobre, Gabriela, et al. "Translating large-scale climate variability into crop production forecasts in Europe." *Scientific Reports*, 2019).

Next to enabling impact-based forecasts, the findings also illustrate the spatial links between regions (where floods or droughts are expected to happen simultaneously), which enables geographic diversification to reduce risks in international portfolios related to, for example, insurance and (food) supply chains.

FROM FINANCING POST-DISASTER RECOVERY TO FINANCING RISKS

While uncertainties in seasonal forecast information remain large, demonstrating the beneficial impacts of acting upon uncertain early warning information may support building confidence in the system.

In my research, I have shown that DRR can be achieved by improving our understanding and prediction of the impacts associated with large-scale climate variability (Guimarães Nobre, Gabriela, et al. "Achieving the reduction of disaster risk by better predicting impacts of El Niño and La Niña." *Progress in Disaster Science*, 2019).

Furthermore, information about climate variability combined with impact-based forecasting can be used to increase the cost-effectiveness of drought risk financing programs. (Guimarães Nobre, Gabriela, et al. "Financing agricultural drought risk through forecast-based ex-ante cash transfers." *Science of the Total Environment*, 2018).

Despite saving lives, providing timely finance before a disaster can be more cost-effective than investing in post disaster expenditures, and may prevent farmers, especially small-scale ones, from falling into poverty.

THERE'S NO BUSINESS LIKE SNOW BUSINESS

AUTHOR
Fabian Willibald

INSTITUTION
Institute of Science, Technology and Policy; Institute of Spatial and Landscape Planning, Eidgenössische Technische Hochschule Zürich (ETH Zürich), Switzerland

BIOGRAPHY
Fabian is currently finishing his Doctoral studies at ETH Zürich. In his research he investigates the vulnerability of mountain destinations toward socio-demographic and climatic changes. He is an expert in climate and hydrological modelling and has published several articles in peer-reviewed journals.

TITLE OF THESIS
Vulnerability of mountain destinations towards socio-demographic and climatic changes

CONTACT
fabian.willibald[at]@istp.ethz.ch

Snow is big business and in alpine regions, tourism and especially ski tourism depend upon it as an important source of economic revenue. Yet, until now, no study investigates the uncertainties and vulnerabilities of the combined effects of climate change and climate variability on winter tourism.

In many parts of the world, nothing says winter quite like a polished run and smooth carve in the middle of a winter wonderland.

Climate change is a major risk that will affect tourism dependent destinations. While the global mean temperature shows a warming of approximately 1° Celsius (33.9 Fahrenheit) over the period from 1880 to 2015, warming over the alpine region – with a maximum of up to 2.5°C - is far more amplified.

With its high dependency on natural resources, most importantly snow, winter tourism is endangered by climate change. Continued warming will cause diverse environmental and socio-economic impacts from regional to global scales and will put the resilience of alpine destinations and their ability to adapt to the test.

VULNERABILITY OF WINTER TOURISM

Record-warm winters, such as in 2006/2007 or 2018/2019 during which skiing was barely possible, might become the new normal. There exist multiple studies investigating the impacts of climate change on winter tourism that highlight the importance of climate variability, weather or extreme events on winter tourism demand, but very few explore this topic in detail.

On shorter timescales, internal climate variability (ICV), defined as natural fluctuations in the climate system that arise in the absence of any radiative forcing, represents the single most important source of uncertainty regarding most climate elements. Yet, no study investigates how climate variability contributes to uncertainties and vulnerabilities in winter tourism.

A reason for the lack of studies is the lack of long-term observations and appropriate climate model data. To make a robust probability assessment of ICV, single model large ensembles (generated by small differences in the models' initial conditions) have been developed. High resolution single model large ensembles are rare, which is why the combined effects of ICV and external forcing on the vulnerability of winter tourism have not yet been studied.

In my research, I use a dynamically downscaled single model large ensemble with 50 members to drive a state-of-the-art, physically based snowpack model for multiple case studies across the Swiss Alps to model daily snow depth. Each ensemble member is exposed to the same external forcing (RCP8.5) but has slightly different initial conditions in the atmospheric model.

The resulting and evolving model spread shows how much the climate can vary because of random internal variations. This makes all 50 members equally likely plausible realizations of climate change over the next century. The simulation period spans from 1980 to 2099, which allows us to analyse more than 5000 years of simulations.

NATURAL AND "FAKE" SNOW

To explore the resilience of the industry through adaptation measures, such as technical snow production, we analysed two setups, one with natural snow only, and one including technical snow. We then calculated a set of socio-economic snow indices to make a probabilistic assessment of the vulnerability of winter tourism toward ICV in a future climate and show the capabilities of technical snowmaking to counter climate change and uncertainties related to ICV.

This setup allows us multiple probabilistic analyses: First, we can classify past extreme winters, such as the record-warm winter of 2006/2007 into the density distribution of the 50 pooled ensemble members for given periods in the present and future. This allows us to compare probabilities of occurrence in the present and in the future.

Second, we can calculate the probabilities that certain indices fall below a critical threshold that does not allow economic viability of ski resorts and we can observe its evolution over time, as well as the adaptability through technical snow production.

Third, we can show how sensitivity toward ICV differs among different socioeconomic indices and between natural and technical snow conditions. Last, we can show how the variability itself might change with anthropogenic forcing, which provides an additional source of uncertainty for the industry.

APPLICATION IN OTHER FIELDS

My application using a single model large ensemble with a high spatial resolution for a probabilistic vulnerability analysis of tourism can be expanded to other fields relevant to the insurance industry, ranging from floods to hail storms and droughts. Given specific general conditions (such as the emissions scenario), it enables a probabilistic analysis of extreme events and an uncertainty analysis of climate variability in the absence of other uncertainties such as model uncertainties.

A first publication summarizing my results was recently published in the *Cryosphere*. A second publication focusing more on the vulnerabilities was recently submitted to *Global Environmental Change*.

THE DESTRUCTIVE POWER OF TROPICAL CYCLONES

AUTHOR
Xiaoning Wu

INSTITUTION
The State University of New York at Stony Brook, NY, U.S.

BIOGRAPHY
Xiaoning is a Ph.D. candidate of Marine and Atmospheric Sciences at the State University of New York, Stony Brook, US. Her research interests include atmosphere-ocean interactions, climate extremes, and disaster risk management. On the theme of climate science and policy, she has worked with the US National Center for Atmospheric Research and specialized agencies of the United Nations. She holds a MSc degree in disaster risks from Beijing Normal University, China, and a BSc degree in Atmospheric Science from Sun Yat-sen University, China.

TITLE OF THESIS
Understanding Hurricane Risks with Simplified Climate Models

CONTACT
xiaoning.wu.1[at]stonybrook.edu

The powerful energetics of tropical cyclones make them one of the world's deadliest and costliest natural hazards, but our understanding of their power is hampered by limited atmosphere and ocean records. Based on years of research, an innovation approach using advanced computing power aims to simplify modelling to shed light on hypotheses concerning tropical cyclones' contribution to ocean heat transport.

Known as hurricanes in the Atlantic or typhoons in the Pacific, tropical cyclones bring high winds, downpours and storm surge to coastlines. In the US in the last three decades alone, hurricanes are responsible for thousands of deaths and $515.4 billion in insured losses [1986-2015].

The cause of the destructive power of hurricanes lies in the energy exchange that occurs at the interface between the atmosphere and ocean. The scientific understanding of tropical cyclone development and feedback to the climate system presents an ongoing challenge for their projection under the changing climate.

ADVANCING THE UNDERSTANDING OF TROPICAL CYCLONE ENERGETICS

Theoretical studies have hypothesized tropical cyclones as an agent of enhancing the poleward heat transport by the ocean and maintaining warm climate states in Earth's history [Cretaceous to Eocene, 146-34 million years ago]. These suggestions are particularly relevant in the context of our warming climate. Improved understanding of these feedbacks will be critical in mitigating tropical cyclone-related climate risks for the current and future climates.

However, observations of tropical cyclones are limited in availability and conventional – or realistic – climate models suffer from their biases in tropical cyclone simulations. Modern records for tropical cyclones have only been kept for about 40 years and available records for the oceans are even far less comprehensive.

With the advances of computational power, global climate models at sufficient resolution [~50 km "pixel size" or finer; see Fig. 1(b)] have become a promising tool to investigate tropical cyclones under past, present and future climates. While the global pattern of simulated tropical cyclones is generally reasonable, biases in tropical cyclone frequency and intensity often persist on the ocean-basin scale [Wu et al., 2018]. In short, the scarcity of observational records and the biases of conventional climate models limit our understanding of the key physical processes of the tropical cyclone-ocean interface.

SIMPLIFYING CLIMATE MODELS

Using simplified climate models, my research offers a physically sound, statistically robust, and computationally efficient method to enhance our understanding of tropical cyclone-ocean interactions.

With an ocean-covered idealization of the Earth, the ocean boundary is represented by a single strip of pole-to-pole continent [Fig. 1(d)]. This design can realistically represent weather systems including tropical cyclones [Fig. 1(e)], as well as key features of the climate system such as atmospheric and ocean heat transport [see Fig. 1(c) and (f); Wu et al. 2020].

Partially due to a larger ocean area, the simplified model generates ~250 tropical cyclones per year, providing a substantially greater sample size for statistical analysis than observation [~90 per year] or conventional climate models [similar to observation or less; Wu et al., 2018]. As a result, the computational costs are reduced by a factor of three compared to conventional climate models solely by sample size.

The experiment design takes advantage of state-of-the-art, high-resolution climate models in innovative ways to address tropical cyclone-ocean interactions. The simplified climate model is developed in the framework of the Community Earth System Model by the US National Center for Atmospheric Research, a participant in international climate assessments.

After a decade-long simulation containing thousands of tropical cyclones, two ocean-only simulation experiments will be conducted with and without filtering tropical cyclone signals from the atmosphere. By comparing the ocean states from these two experiments and focusing on oceanic processes with and without tropical cyclone impacts, the hypotheses on tropical cyclones' contribution to ocean heat transport will be verified.

IMPACTS: ADVANCING CLIMATE SCIENCE AND MODELING FOR DISASTER RISK MANAGEMENT

Scientifically, the expected results will clarify the impact of tropical cyclones on the energetics of the climate system. Through the investigation of tropical cyclone-induced processes of atmosphere-ocean energy exchanges, my research will provide new perspectives on the question of tropical cyclones' feedback to the climate system, advancing our process-level understanding from previous observational and conventional climate modelling studies.
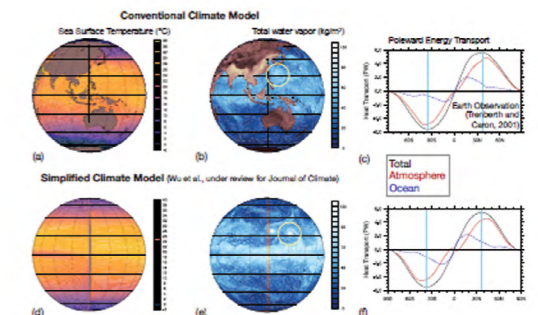
Fig. 1. *The capacity of simplified climate models (bottom row) – with idealized land and ocean [Panel (d)] – to capture tropical cyclones [Panel (e)] and the large-scale climate characteristics such as poleward energy transport [cf. Panel (f) and observation in Panel (c); Wu et al., 2020]. In contrast, conventional, realistic climate models (top row) requiring complex land and ocean setup [Panel (a)] are known to exhibit persistent biases in simulated tropical cyclone frequency and intensity [Wu et al., 2018].*

More broadly, the simplified climate modelling approach can unlock new potential from state-of-the-art climate models to inform disaster risk management under climate change, including catastrophe modelling.

The versatility of simplified climate models enables its application toward various climate hazards under climate change scenarios, generating larger sample sizes at lower computational costs than conventional climate models allow. Moreover, the idealized model design facilitates the physical interpretation of the simulated results. This combination of large datasets and physical insights can serve as sought-after foundations for contemporary statistical modelling approaches, including knowledge-guided machine learning.

Therefore, by combining the respective strengths of physical and statistical modelling, the introduction of simplified climate models into catastrophe modelling holds the promise of addressing some long-standing questions for (re)insurers in light of climate change, which will support climate risk management with the best available climate science.

HIGH WATER MARKS

AUTHOR
Parisa Hosseinzadehtalaei

INSTITUTION
Catholic University of Leuven, Belgium

BIOGRAPHY
Parisa obtained her Ph.D. in September 2020 from the Catholic University of Leuven in Belgium. She currently works at the same University as a postdoctoral researcher in the Department of Civil Engineering. For her postdoctoral research, she will continue to build on her previous research on the impact analysis of climatic and socioeconomic changes on extreme events that will allow her to address additional questions on flood risk assessments over Europe. Parisa has published several papers in top international peer-reviewed journals in the research field. Her innovative work on future flood risks over Europe has received 2019 Travel Award from Water journal. She has authored or co-authored more than 80 publications of which 47 in peer-reviewed international journals.

TITLE OF THESIS
Risk assessment of future flood events over Europe under climatic and socio-economic changes

CONTACT
parisa.hosseinzadehtalaei[at]kuleuven.be

Europe faces increasing flood risk because of the changing environment. This research develops a novel alternative to the computationally expensive continental flood simulations by using a satellite-based data driven method.

"That was a one-in-100-year flood," said a shocked resident of Schönebeck, near the east German city of Magdeburg. She was assessing damage from flooding of the Elbe River that had put the village all but totally under water in 2013.

A one-in-100-year flood may sound a rarity but is not. The phrase describes the 1% chance that a hazard event has of happening in any year. One-in-100-year events can happen more regularly, and, for residents of Magdeburg, the last flood was well within living memory. The previous time the Elbe had overflowed was only in 2002, also with devastating consequences.

Extreme precipitation (rain, snow, sleet or hail) and floods are prominent among the major climate-related disasters that cause thousands of fatalities and billions of euros in damages each year. Unfortunately for residents of cities like Magdeburg, the risk of such flood is expected to increase significantly under changing climatic and socioeconomic conditions. These events will place increasing pressure on vulnerable societies and ecosystems.

Advance planning and management strategies will be indispensable to limit flood damage and to create resilient, future-proof cities. As a result, strategic risk assessments, such as the supranational flood risk reduction policy introduced in Europe under the Floods Directive of 2007, have drawn attention by providing important applications for flood risk management and increasing public awareness of flood risk.

Such approaches also provide the insurance sector with location-specific assessments of risk to predict probable losses more accurately. This enables insurance premiums to be estimated to minimize unforeseen losses and reduce price quickly, confidently and competitively. In this way, assets, properties and services will be protected against future floods.

SATELLITE DATA-DRIVEN QUANTIFICATION OF FLOOD HAZARDS

Despite the importance of flood risk assessment, the number of large-scale studies remains limited. This is primarily due to the high computational cost of continental or global flood simulations. A resource- and cost-efficient alternative is developing data-driven methods based on satellite imagery and remote-sensing techniques, which was the focus of the research.

Satellite data provide climate (for example, rainfall) and spatial (for example, Digital Elevation Model: DEM, Impervious surface) data at fine spatial and temporal scales as inputs for flood modelling next to flooded area delineation and flood damage assessment.

This research develops a novel alternative to the computationally expensive continental flood simulations by using a satellite-based data driven method that makes use of CMORPH (Climate Prediction Center Morphing method) hourly precipitation, impervious surface data and digital elevation model (DEM) (See Hosseinzadehtalaei, P., Tabari, H., Willems, P. (2020) "Satellite-based data driven quantification of pluvial floods over Europe under future climatic and socioeconomic changes." *Science of the Total Environment,* 721, 15, 137688).

VULNERABILITY OF WATER INFRASTRUCTURE

The results show that extreme precipitation events will be amplified by the end of this century and their frequency will triple (Hosseinzadehtalaei, P., Tabari, H., & Willems, P. (2019) "Regionalization of anthropogenically forced changes in 3 hourly extreme precipitation over Europe." *Environmental Research Letters*, 14(12), 124031). As a result, the risk of flooding is also expected to increase.

Flood risk, a product of hazard and exposure-vulnerability, is projected to increase up to 87% across Europe (Hosseinzadehtalaei, P., Tabari, H., Willems, P. (2020) "Satellite-based data driven quantification of pluvial floods over Europe under future climatic and socioeconomic changes." *Op. cit.*).

Spatially, the eastern and southern parts of Europe (Greece, Italy, Bulgaria, North Macedonia, Romania) will face the highest risk of pluvial floods. A fossil-fuel based development in the future would lead to 14–15% higher flood risk compared to a sustainable development.

The shift in socioeconomic and climatic pathways is more influential in north Europe, with a risk reduction potential of 20–23%. The results also reveal that the amplified future flood risk is predominantly driven by climate change rather than socioeconomic drivers.

Accordingly, critical precipitation events used to flood control structures and urban water infrastructure will intensify (Hosseinzadehtalaei, P., Tabari, H., Willems, P. (2020) "Climate change impact on short-duration extreme precipitation and intensity–duration–frequency curves over Europe." *Journal of Hydrology*, 590, 125249).

This implies that existing sewer systems are insufficient to deal with future extreme precipitation events. The efficiency of storm water facilities (sewers, storm water management ponds, street curbs, swales) will be affected; likely leading to a decrease in their level of service and to more frequent urban flooding.

This is important in urban areas where the failure risk of existing infrastructure can cascade owing to extensive interconnections between different infrastructure systems. The expected changes in precipitation, namely in terms of intensity, duration and frequency, must be incorporated for the future design of urban water systems, as well as in adaptation planning.

In order to create resilient societies, proper adaptation strategies must be implemented to reduce the breakdown risk of infrastructure systems and dependent subsystems in urban areas. To avoid lock-in inflexible strategies and decrease the risk of decision failure regarding the evolving nature of risks, capacity building, win–win or low-regret, synergy options or iterative adaptation pathways must be undertaken.

To diminish future flood risk over Europe, priority should be given to reduce climate change-induced flood intensification, which demands a global effort, along with the reduction of social and agricultural vulnerabilities. New tools such as micro insurances and nature-based solutions are among disaster risk reduction (DRR) efforts to reduce future flood risk in Europe.

FUTURE FLOODING: LET'S NOT RISK IT

AUTHOR
Clare Stephens

INSTITUTION
University of New South Wales (UNSW), Australia

BIOGRAPHY
Clare is a postdoctoral researcher with the UNSW Water Research Centre in Sydney. Her key interest is hydrology under climate change, with a focus on modelling and data analysis. She obtained her Ph.D. in 2020 from UNSW, researching the performance robustness of hydrologic models in a changing environment. Clare was selected as a Westpac Future Leaders scholar in 2016 and the Young Environmental Engineer of the Year (Engineers Australia) in 2015. Before starting her research career, she was a consulting engineer working on flood risk management and infrastructure design projects.

TITLE OF THESIS
Accounting for changing catchment conditions in engineering tools for flood risk management

CONTACT
clare.stephens[at]unsw.edu.au

By translating cutting-edge science into practical guidance for engineers, we can better manage the effects of climate change on flood risk.

The region of Southeast Queensland lies on Australia's eastern coast and is home to over 3 million people. Over December 2010 and early January 2011, the area experienced widespread rainfall. Then, on January 10, a torrential downpour fell onto the already saturated landscape across the Darling Downs.

The result was devastating flooding. In the city of Toowoomba, a "wall of water" washed away cars and drowned four people within hours. In the small town of Grantham, entire houses were carried off in what the Premier described as an "inland tsunami."

Over the next two days, floodwaters reached the larger cities of Ipswich (pop. 200,000) and Brisbane (pop. 2.5 million), where I grew up. My family, including relatives visiting for Christmas, was evacuated by boat through the streets of our neighbourhood. Many of our neighbours were among the 20,000 people left homeless after the waters receded.

Flooding drives massive destruction throughout the world, accounting for a third of all monetary losses from natural disasters globally. Fortunately, effective infrastructure and planning solutions are available to protect cities and communities. These include flood mitigation dams and detention basins; drains and levees; individual building upgrades; planning controls on floodplain development and relocation of at-risk communities.

While these measures can provide substantial benefits, they often come with high initial costs. As engineers, it is our responsibility to avoid wasting time and money on strategies that are not fit-for-purpose. It is difficult to change the size of structural measures (for example, dams and levees) after completion, so we need to design them well upfront to perform for many years into the future. This task is particularly challenging because it requires understanding how flood risk might evolve in coming decades due to climate change.

WHAT DRIVES CHANGING FLOOD RISK?

There are three main factors changing flood risk over time. The first is rising extreme rainfall intensities. This is expected theoretically (because a warmer atmosphere can hold more moisture) and increasingly supported by empirical evidence around the world. The second is changing land use. For example, urbanization is associated with increased flood risk downstream. Current engineering flood models can account for both of these factors. However, changes in the third dynamic factor, the wetness of the catchment before a flood event, are not well understood or considered in engineering practice.

The status of a catchment before a flood-generating storm (termed "antecedent conditions") has a large effect on the size of a flood. In fact, major floods are often generated by less extreme rainfall events if the catchment is already particularly wet. Conversely, if the catchment is initially dry, extreme rainfall events may not lead to flooding.

The likelihood of experiencing wet or dry conditions before a storm depends on seasonal and average rainfall in the region, as well as evaporation rates. As these variables shift under climate change, so too will antecedent conditions and hence flood magnitude. Failing to account for changing antecedent conditions in engineering models leads to mischaracterized future flood risk, limiting our ability to respond appropriately and possibly leading to maladaptation.

HOW COULD ENGINEERING PRACTICE BE IMPROVED?

Antecedent conditions are typically accounted for in engineering models through a parameter called 'initial loss.' Wet antecedent conditions are represented by small loss parameters leading to large flood volumes relative to rainfall. Changes in typical catchment conditions due to climate change could lead to biased initial loss estimates and poorly constrained future flood analyses.

Previous research (Stephens, C. M., Johnson, F. M., & Marshall, L. A. (2018). "Implications of future climate change for event-based hydrologic models." Advances in Water Resources, 119, 95-110) has shown that failing to account for changing initial loss values was the main reason a flood model performed poorly under sustained drying for a large Australian catchment.

Hydrologic researchers often use more complex models than practicing engineers, including models that can explicitly represent changing catchment conditions over time. However, these models require a lot of data and cannot be used in most applied engineering work.

Our current research uses innovative model comparison techniques to select better initial losses in the simpler engineering flood models. The comparisons will be repeated across different catchments, climate zones and future scenarios to understand patterns in changing initial loss parameters. By uncovering these systematic parameter shifts as rainfall and evaporation regimes evolve, we can develop engineering tools for better characterizing future flood risk.
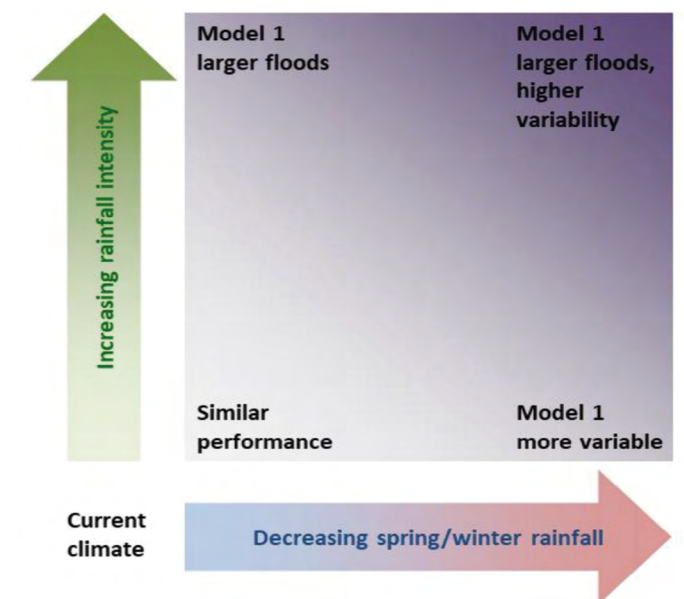
Fig 1: *Model Intercomparison example, based on Stephens et al. (2018)*

The science around climate change has advanced at an astonishing pace in recent decades. Every year we learn more about the complex shifts emerging in the atmosphere and across landscapes, with broad consequences for human society.

However, we have often been slow to translate this knowledge into the applied tools that engineers use every day, which limits our ability to plan for the future we know is coming. By better representing climate change effects in the models behind most real-world flood planning, we can engineer a safer water future.