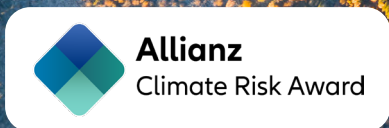




Pathways to Resilience

Mitigation and Adaptation in a Changing Climate

A compendium of essays for the
Allianz Climate Risk Award 2024



November 2024
Munich, Germany

About the compendium

Launched in 2017, the Allianz Climate Risk Award celebrates scientists at the start of their careers and whose work sheds light on the nexus between climate change and extreme weather events. The award is open to PhD candidates and Post-Doctoral researchers whose research focuses on: Reducing the risk of extreme weather events that are intensified by climate change and fostering resilience by applying technological solutions.

The compendium is a compilation of selected essays based on the criteria of innovation, research excellence, applicability and impact from applicants of the 2024 Allianz Climate Risk Award. This compendium is issued online only and is published exclusively for didactic purposes.

Important Information

The Allianz Group does not assume liability for the accuracy or completeness of the content, nor does the Allianz Group assume a responsibility to ensure the content remains up-to-date. The authors' opinions are not necessarily those of the Allianz Group.

Table of Contents

→	Foreword	06
01	Fighting fire with data A machine learning approach that offers real-time fire danger forecasts.	08
02	Droughts without borders: Mapping global agricultural hotspots Extreme weather events, particularly droughts, significantly threaten global agricultural production. The climate crisis exacerbates this by making events more frequent, severe and unpredictable. This innovative analysis provides vital insights for coordinated adaptation strategies to mitigate the devastating effects of drought on food security and livelihoods.	10
03	Forecasting fury: Unraveling the secrets of a violent sky Hailstorms are increasingly destructive, causing billions in damage annually. With the climate crisis driving their frequency and intensity, new research integrates machine learning and real-time data to advance risk assessment and improve predictions.	12
04	When it rains, it pours: The growing impact of extreme weather on the UK The UK's wettest 18 months on record have highlighted a worrying trend of increasingly severe winters driven by natural variability and climate change. As storms intensify and flood risks rise, new research reveals that traditional climate models may underestimate the true scale of future rainfall.	14
05	On sliding ground: Urban sprawl and increased flood risk are driving slow-moving landslide exposure Entire towns and villages could be unknowingly situated on slow-moving landslides, yet a comprehensive global overview of this risk has been elusive. Research shows that one in ten landslides could be inhabited and driven by urban expansion and flood exposure.	16
06	The chances and limits of on-farm crop diversification to cope with drought risk Drought events are a leading cause of substantial crop yield losses, posing significant risks to food security and farmers' incomes. One commonly employed risk management strategy to combat these drought impacts is on-farm crop diversification, which involves growing multiple crops simultaneously during a cropping season.	18
07	Predicting the unpredictable Despite advancements in climate modeling, existing models struggle to capture the intricate dynamics of tropical cyclones.	20
08	Winds of change in tropical cyclone modeling Future tropical cyclone risks will depend on the complex interplay of climate change and socioeconomic development, both introducing substantial uncertainties.	22
09	Riding out the storm: Proactive urban planning for catastrophic flood resilience Western Europe has experienced catastrophic floods that far exceed official hazard map predictions. In 2021, rivers burst their banks, dams and dikes were pushed to the brink and entire regions were overwhelmed.	24
10	Global multi-hazard risk assessment in a changing climate Risk assessments often overlook the interconnected nature of climate-related events, potentially leading to underestimations or inefficient resource allocation. By acknowledging these interdependencies and considering recovery dynamics, we can more effectively manage risk in the face of evolving climate and socioeconomic conditions.	26

Locations of the contributors and their research fields

Hailstorms are causing billions in yearly damages. The US alone sees over \$10Bn in annual losses from severe storms, impacting agriculture, infrastructure, and property. Despite their devastating effects, hailstorms remain poorly understood due to inconsistent data and the complexity of the atmospheric processes that drive them. New research integrating machine learning and real-time data offers hope for advancing risk assessments and prediction, helping to mitigate the damage and enhance community resilience.

Droughts are a leading cause of severe crop yield losses, threatening food security and farmers' incomes. Crop diversification, the practice of growing multiple crops in a season, is a crucial strategy to manage this risk, though its effectiveness varies with drought severity and crop types. As extreme droughts increase due to climate change, understanding the most resilient crop combinations is vital for better risk management and policy decisions.



Icía Guerrero Calzas

Nationality: Spain

Location: Spain



James Carruthers

Nationality: British

Location: United Kingdom



Supriya Krishnan

Nationality: Indian

Location: The Netherlands

Climate chaos is making flooding more frequent and destructive, with rising temperatures leading to heavier rainfall, higher sea levels and stronger storm surges. Traditional flood defenses like dikes and seawalls, are increasingly inadequate in the face of extreme events, revealing the need for more holistic strategies. For instance, despite the Delta Programme's extensive flood defenses in the Netherlands, recent extreme weather exposed critical vulnerabilities. In the UK, the wettest 18 months on record (October 2022 to March 2024) brought severe storms like Babet and Gerrit, causing millions of euros in damages.



Joseph W Lockwood

Nationality: United States of America

Location: United States of America



Simona Meiler

Nationality: Swiss

Location: Switzerland

Tropical cyclones are highly destructive, causing severe damage, loss of life and massive economic costs. Yet, predicting their behavior remains challenging due to the complex dynamics within the storms, especially during extreme events. Accurately forecasting cyclone intensity and track is critical for disaster preparedness and minimizing impacts on vulnerable communities. Future cyclone risks also depend on the uncertain interplay of climate change and socioeconomic factors, making robust risk assessments essential.

Risk assessments often miss the interconnected nature of climate events, leading to underestimated risks and wasted resources. By focusing on hazards in isolation, we overlook how events like El Niño can cause floods in one region and droughts in another. It's crucial to recognize these interdependencies and adjust recovery plans and resource allocation accordingly.

Drought is responsible for about 34% of crop and livestock losses in developing nations, and these impacts often span across borders, making collective action crucial. By mapping global hotspots where droughts are most likely to co-occur provides insights for coordinated adaptation. By analyzing global data on extreme drought events, it is possible to highlight areas of heightened risk to help policymakers, farmers, and insurers better manage systemic drought risks.

Jonas Schmitt
Nationality: Swiss
Location: Germany



Zélie Stalhandske
Nationality: Swiss
Location: Switzerland



Harold Armando Achicanoy Estrella
Nationality: Columbian
Location: The Netherlands



Joaquin Vicente Ferrer
Nationality: Philippines
Location: Germany



Urban sprawl and climate change are driving an alarming rise in landslide risks as communities expand into unstable, hilly regions. Studies reveal that one in ten landslides may affect inhabited areas, especially in mountainous regions where towns often sit unknowingly on slow-moving, unstable ground. These landslides can shift gradually for years, but when they collapse, the devastation is swift and catastrophic, destroying entire villages in minutes. With landslides claiming 4,500 lives and causing \$20Bn in damages annually, the urgency for better global oversight and mitigation is undeniable.

Alberto Ardid
Nationality: Venezuelan
Location: New Zealand



A 2022 UN report projects a 30% rise in extreme wildfires by 2050, underscoring the importance of improved prediction tools to protect ecosystems, property and lives. Machine learning-based approaches address this by offering high-resolution, real-time wildfire danger forecasts. Unlike traditional methods, which struggle to capture the full complexity of factors like climate, vegetation and land use, these can leverage real-time weather data to deliver sub-hourly predictions, providing a more accurate and adaptive tool for fire management agencies.

Foreword

Introduction Compendium 2024



**HOLGER TEWES-
KAMPELMANN**
(CEO Allianz SE Reinsurance)

Since 2017, Allianz Re has proudly supported brilliant young researchers working on climate challenges through the Allianz Climate Risk Award, recognizing the urgent need to address the increasing risks posed by extreme weather. This initiative reflects Allianz's deep commitment to bridging the gap between academia and the insurance industry, fostering collaborations that benefit the generations to come.

As insurers, we depend heavily on the latest climate science to continually refine our underwriting processes, especially given the rising frequency of natural disasters. Extreme weather events, intensified by the climate disaster, are occurring in regions that previously had low exposure, and this trend presents significant challenges. Understanding how these shifts will shape future risks is critical, and our ongoing dialogue with scientists plays a crucial role in creating pathways to resilience to mitigate and adapt to the climate chaos.

Supporting knowledge

The Allianz Climate Risk Award is part of a broader strategy to encourage innovation that aligns with the insurance industry's future needs. The Award has successfully spurred collaboration between academic researchers and our internal catastrophe (Cat) specialists, transforming scientific insights into practical applications that benefit both parties. These collaborations are essential as they allow us to translate scientific knowledge into risk management solutions that improve the resilience of our clients and the broader market.

For the 2024 Climate Risk Award, the researchers have focused on topics like climate change attribution, peril correlations and the adaptation of critical infrastructure to climate risks. Among the papers submitted, the devastating European floods of July 2021 continue to drive research on disaster mitigation. Preventing crop yield losses and measuring and predicting tropical cyclones are other themes. The underexplored threat of landslides is also featured.

Landslide risks are growing due to urban expansion into hilly areas and more frequent heavy rainfall caused by climate change. Improved mapping and understanding of these risks could help safeguard vulnerable communities. We are thrilled to continue working with researchers on these important subjects, as they hold the key to developing more effective risk models and mitigation strategies.

Preparing for a climate-challenged future

Climate change presents one of the most pressing challenges of our time. At Allianz, we recognize that preparing for the future means building resilience today. This requires not only the latest data and models but also the creativity and expertise of the scientific community. By fostering stronger partnerships with researchers, we are better equipped to respond to the growing risks that climate change brings.

Through initiatives like the Allianz Climate Risk Award and Research Grant, we are committed to deepening our ties with academia. We can create pathways to a more resilient future for the insurance industry, our clients and the global community by continuing to work together.



Fighting fire with data



Author

Alberto Ardid

Institution

University of Canterbury, New Zealand

Biography

Alberto is a researcher with a PhD in Engineering Science from the University of Auckland. He holds an MSc and BSc in Geophysics from the University of Chile. He is employed as a Post-Doctoral Research Fellow at the University of Canterbury, New Zealand, developing real-time forecasting models for natural hazards such as volcanic eruptions, wildfires, floods and avalanches. His work utilizes cutting-edge machine-learning techniques and real-time data to enhance the accuracy and applicability of hazard forecasts, particularly in resource-limited regions.

Prior to his current role, Alberto worked as a Project Geophysicist at NGA in Chile, focusing on geophysical exploration and consultancy projects. He also has experience as a Seismic Data Analyst at Spectrum Geo in the United Kingdom, where he processed seismic reflection data for geological interpretations. His early career included leading translation projects in the mining and energy sectors, demonstrating his diverse skill set.

Title of thesis

Affordable Fire Danger Forecasting: AI Transfer Learning for Resource-Limited Regions

Contact

alberto.ardid(at)canterbury.ac.nz

A machine learning approach that offers real-time fire danger forecasts.

Due to the climate crisis, wildfires are becoming increasingly frequent and severe, threatening ecosystems, property and human lives. According to a 2022 UN Environment report, the number of extreme wildfires is projected to increase by 30% globally by 2050. This alarming trend suggests that more intense fires may occur in traditionally fire-prone environments and in regions previously unaffected by such hazards. The urgency of these changes highlights the critical need for advanced wildfire danger forecasting to help fire management agencies allocate resources effectively to high-risk areas.

Innovative AI for wildfire prediction

Wildfire danger results from complex climate, vegetation, land use and weather interactions. Recognizing that traditional forecasting methods often struggle to consider all these parameters in real-time, we have developed an advanced machine learning-based approach that enhances wildfire predictions' precision, reliability and speed.

Our model uses real-time weather data to predict fire danger on a sub-hourly basis, improving existing systems without compromising applicability in resource-limited regions. By capturing the interactions of the factors, our approach offers a more nuanced understanding of wildfire risks.

Challenges with traditional forecasting

Current fire danger indices, like the Canadian Fire Weather Index and the Australian Forest Fire Danger Index, often lack the temporal resolution and predictive accuracy required for timely interventions, particularly in regions with scarce historical weather and fire data. Rapidly developing pre-fire weather conditions can lead to unexpected wildfires, risking lives and property.

Our solution addresses these challenges by training AI models in data-rich environments, such as Southeast Australia, and applying them to areas with limited historical data. This ensures timely and accurate forecasts even in data-scarce regions.

Harnessing real-time data for precision forecasting

Our model employs real-time data from standard weather stations, analyzed at a sub-hourly resolution. Using time series feature engineering, we identify distinct weather patterns occurring hours to days before a wildfire. We train random forest algorithms to classify pre-fire weather conditions within one to five days before recorded fire events. The model outputs a continuous time series of fire likelihood, updated every 30 minutes with new meteorological data. The dynamic monitoring system is a robust tool for early warning of fire danger.

The first generation model (tested with historical weather and fire data from Queensland, Australia) achieved a 47% improvement in predicting critical pre-fire conditions compared to the existing Forest Fire Danger Index (FFDI). This enhanced predictive capability supports more effective fire suppression and timely evacuations, ultimately reducing the risk to life and property.

Overcoming data scarcity

We employ transfer learning techniques to address data scarcity, especially in low-income countries experiencing wildfire risks due to climate change. By transferring knowledge from data-rich regions like Australia to data-scarce areas such as the Miombo woodlands in Africa, the Himalayan region, and parts of the Amazon rainforest and Central Chile, we create accurate forecasting models even where historical data is limited.

Our model is designed to be cost-effective and scalable, making it accessible for communities and agencies with limited resources. Using low-cost weather stations and cloud-based computational resources, we ensure real-time data processing and updates every 30 minutes. This enhances wildfire danger assessment in resource-constrained environments, supporting better preparedness and response.

Future directions and broader implications

The implications of our research extend beyond fire management. Accurate and timely wildfire danger forecasts enable decision-makers to implement timely evacuations and effective fire suppression measures, mitigating immediate impacts and contributing to long-term resilience. As the climate crisis continues to alter fire regimes globally, dynamic and responsive forecasting tools like ours are increasingly vital.

Looking ahead, we are developing similar models for hazards, such as floods, using rainfall and flow data to create multi-hazard risk metrics. This aims to improve extreme weather forecasting in data-poor regions, supporting more informed decision-making and disaster preparedness.

Our machine learning-based danger forecasting system advances wildfire management. By integrating advanced data analytics and real-time weather monitoring, we can predict and respond to wildfire threats more effectively, protecting communities and ecosystems from the devastating impact of natural disasters.

Real-Time Implementation and Early Warning Model

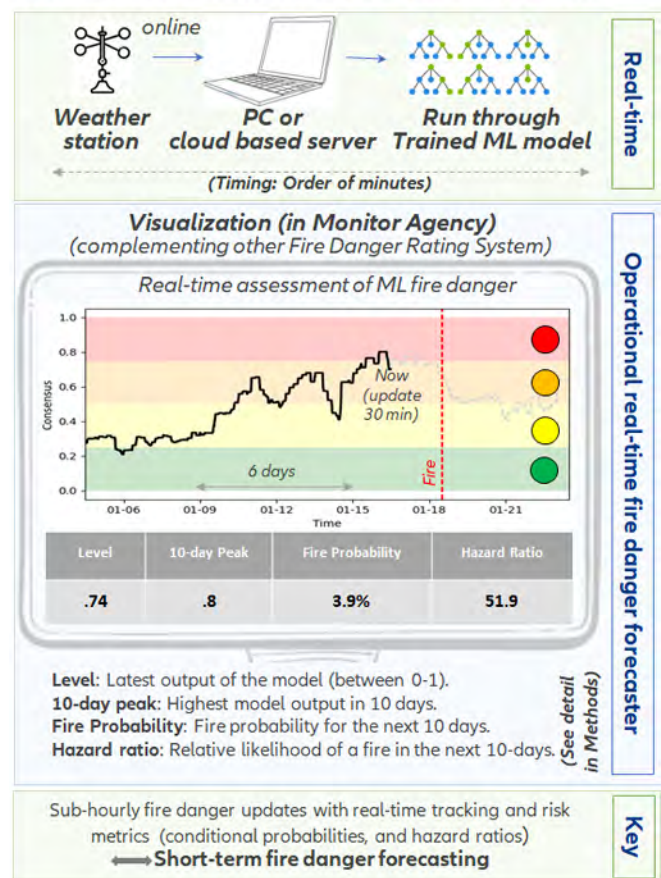


Figure 1: This illustrates the workflow for generating real-time fire danger forecasts using a trained machine-learning model. Weather data is continuously gathered from weather stations and transmitted to a local PC or cloud-based server. The trained ML model then processes the data, which updates every 30 minutes. The trained model processes the incoming data every 30 minutes, analyzing it to produce a consensus value that indicates the current fire danger level within minutes. This real-time assessment is integrated into a monitoring agency's system, enhancing existing fire danger rating methods with dynamic, sub-hourly updates. The visualization highlights critical metrics such as: current danger level, ten-day peak forecast, fire probability and the hazard ratio, a metric indicating the relative likelihood of a fire compared to average conditions.

Droughts without borders: Mapping global agricultural hotspots



Author

Harold Armando Achicanoy Estrella

Institution

Wageningen University and Research,
The Netherlands

Biography

Harold is a researcher at the Alliance of Bioversity International & CIAT and a PhD candidate at Wageningen University and Research. He specializes in risk management and resilience and focuses on developing financial solutions to address the impacts of the climate crisis. He holds a BSc in Statistics and an MSc in Computer Science, bringing a robust quantitative background to his work. With over 11 years of experience at the Alliance of Bioversity International & CIAT, Harold has expertise in climate change impacts, crop modeling and geographical information systems.

His research aims to innovate agricultural insurance through data-driven approaches, particularly in weather index-based insurance (WII) and picture-based insurance (PBI). Harold's work identifies global regions where WII can effectively mitigate the risks of extreme droughts while also addressing the challenge of basis risk – a critical barrier to WII adoption.

Title of thesis

Data-driven innovations for improving climate risk management at the global scale

Contact

harold.achicanoyestrella(at)wur.nl

Extreme weather events, particularly droughts, significantly threaten global agricultural production. The climate crisis exacerbates this by making events more frequent, severe and unpredictable. This innovative analysis provides vital insights for coordinated adaptation strategies to mitigate the devastating effects of drought on food security and livelihoods.

Droughts are among the major causes of crop and livestock production losses, contributing to approximately 34% of such losses in the least-developed countries (LDCs) and low- and middle-income countries (LMICs).¹ These losses have lasting consequences for food security and livelihoods, often spanning across vast areas and crossing national country borders. To effectively coordinate adaptation efforts among policymakers, farmers, and insurers, it is crucial to understand the spatial dependence of agricultural drought extremes.

Our research investigates the global spatial dependence of extreme agricultural drought events by identifying spatial clusters where these events are likely to co-occur. We have developed an [interactive global map](#) to visualize these clusters, making our findings accessible to stakeholders. Our results are vital for governments and extension services to coordinate adaptation strategies. Moreover, our results provide insurers with insights into systemic drought risk clusters, enabling better diversification opportunities for re-insurers.

We analyzed the spatio-temporal patterns of the Standardized Precipitation and Evapotranspiration Index (SPEI) for all arable areas globally. This analysis identifies extreme drought events within agricultural growing seasons, both temporally and spatially. Using an extreme value clustering approach, we delineate spatial clusters where extreme droughts tend to occur concurrently. Furthermore, we identified hotspot clusters where extreme drought events have become more frequent between 1980 and 2022, showing high crop and livestock exposure levels. We recommend prioritizing adaptation efforts in these hotspot clusters.

1. <https://www.fao.org/interactive/disasters-in-agriculture/en/>

Overall, we identified 456 spatial drought clusters worldwide (Figure 1). Our analysis reveals substantial opportunities for transnational collaboration, as these extreme drought clusters do not restrict themselves to country borders or agroecological zones. The potential for transnational collaboration is particularly high in Africa (76.6% of clusters span multiple countries), Europe (64.6%), South America (49.3%), Asia (47.3%), North America (40.3%) and Oceania (8.3%).

Critical findings for crop and livestock production:

- **Crop production:** We identified 39 critical hotspot clusters that require immediate attention. These are distributed as follows: Africa (46.2%), Asia (25.7%), Europe (15.4%), South America (10.3%), and North America (2.6%).
- **Livestock production:** We identified 25 critical hotspot clusters for livestock, distributed across Asia (32%), South America and Africa (28% each), North America (8%) and Europe with one hotspot cluster.

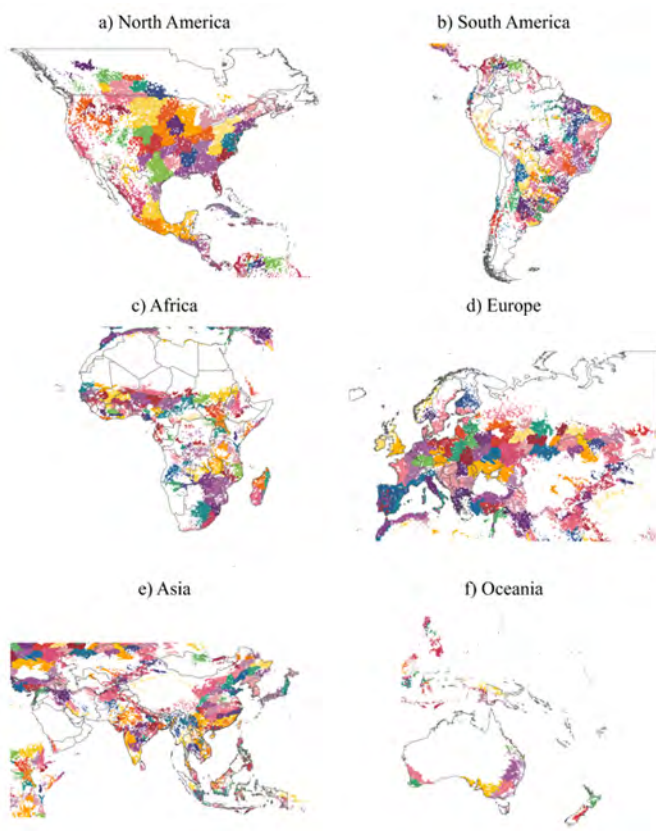


Figure 1: Spatial Clusters of Agricultural Extreme Drought Events in Arable Lands

This figure illustrates spatial clusters where extreme droughts co-occur within arable lands during growing seasons. Distinct colors distinguish the clusters.

Our findings demonstrate that extreme agricultural droughts transcend political borders and agroecological zones. Therefore, adaptation efforts should be coordinated within these identified spatial clusters rather than at the national level. Transnational climate change adaptation initiatives are crucial for developing joint solutions for farmers with similar drought exposure risks.

Existing initiatives such as AICCRA² in Africa, Climate-ADAPT³ in Europe and global-scale programs like Insuresilience⁴ and RegionsAdapt⁵ provide a foundation for such collaborative effort. We recommend synchronizing adaptation strategies, such as modifying planting dates, developing drought-resistant crop varieties, introducing new crops, planning and implementing insurance schemes, enhancing irrigation infrastructure and integrating crop-livestock systems within these clusters.

For agricultural insurers, our results highlight a significant opportunity to pool farmers from different clusters to minimize systemic risk – reducing the likelihood that all farmers will need insurance payouts simultaneously. Our methodology can also be adapted to assess other risks, enabling more precise quantification and management of systemic risks across agricultural portfolios. Finally, this approach can lower insurance premiums, making coverage more affordable for farmers and enhancing their resilience to extreme drought.

2. <https://aiccra.cgiar.org/>
 3. <https://climate-adapt.eea.europa.eu/en>
 4. <https://www.insuresilience.org/>
 5. <https://regions4.org/regionsadapt/>

Forecasting fury: Unraveling the secrets of a violent sky



Author

Icíar Guerrero Calzas

Institution

Universitat Autònoma de Barcelona
(In collaboration with Mitiga Solutions S.L.), Spain

Biography

Icíar is an early-stage researcher at the Universitat Autònoma de Barcelona, specializing in the intersection of meteorology, physics and computer science. As a member of the High-Performance Computing Applications for Science and Engineering (HPCA4SE) research group, Icíar is pursuing an Industrial PhD funded by AGAUR, where she focuses on integrating machine learning with numerical weather prediction to improve hailstorm risk assessments.

Collaborating with Mitiga Solutions SL, her research aims to bridge the gap between academic innovation and industry application, tackling real-world challenges with advanced computational techniques. Driven by a commitment to impactful research, Icíar's work exemplifies the fusion of scientific inquiry and practical problem-solving, contributing to enhanced climate resilience and risk management.

Title of thesis

Understanding and mitigating hailstorm risks through technological innovation

Contact

iciar.guerrero(at)autonoma.cat

Hailstorms are increasingly destructive, causing billions in damage annually. With the climate crisis driving their frequency and intensity, new research integrates machine learning and real-time data to advance risk assessment and improve predictions.

In the summer of 2022, Catalonia experienced catastrophic hailstorms that shattered windows, damaged vehicles and destroyed crops, leading to millions of euros in losses and significant disruptions.¹ This event highlighted a troubling trend: the increasing frequency and intensity of extreme weather events driven by climate change. Hailstorms, in particular, pose a substantial risk due to their ability to inflict severe damage over a short period.

In the United States alone, severe storms result in annual economic losses exceeding \$10Bn, affecting agriculture, infrastructure and personal property.² Despite their significant impact, hailstorms remain poorly understood due to inconsistent data and the complex atmospheric processes involved. Addressing this knowledge gap requires innovative approaches to improve our understanding and mitigate hailstorm risks, ultimately enhancing community resilience and minimizing adverse impacts.

The challenge of predicting hailstorms

Hail forms when strong updrafts within storm clouds lift water droplets to altitudes where they freeze, growing into ice balls or irregular shapes that eventually fall as hail. While the general conditions for hail formation are well-known, accurately predicting hailstorms' timing, location and size remains challenging.

Weather models, such as the Weather Research and Forecasting (WRF) model, provide detailed forecasts but often struggle with simulating the specific conditions leading to hailstorms. A critical aspect of risk assessment is predicting hailstone size, as larger hailstones cause more severe damage.³ However, the computational requirements and costs associated with these simulations add to the complexity of predicting hailstorms.⁴

Additionally, the lack of validated, direct observations of hail – due to its infrequent occurrence – further complicates data collection and analysis. While radar and satellite data are also used for predictions, these have limitations and often do not cover remote areas well, leaving some hailstorms undetected.

Advancing hailstorm risk assessment with technology

Our research integrates real-time data from weather radars and ground-based observations with advanced machine learning techniques to enhance hailstorm risk assessment. High-Performance Computing (HPC) has effectively identified hailstorm-prone areas, but its costs limit widespread use. To overcome this, we combine machine learning techniques with traditional weather models to reduce costs and enhance prediction accuracy.

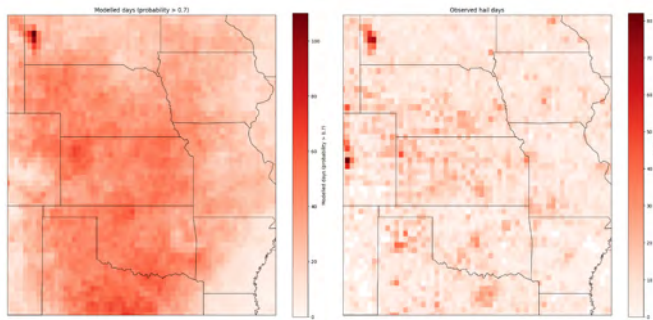


Figure 1: Application of the CDD model in Central US compared with reported observations

We use a decision tree-based model with a framework for identifying factors contributing to hailstorm formation. A key innovation is our Convective Days Detector (CDD), a machine learning model trained on observational and reanalysis data to estimate the daily probability of convective events at specific locations. The CDD allows us to pinpoint days with a higher likelihood of hail. Our model aligns with observed seasonal patterns of convective activity, accurately predicting peaks during periods of heightened convective storm activity (Figure 2). It performs well across cities with diverse weather patterns, demonstrating its adaptability to various climatic conditions.

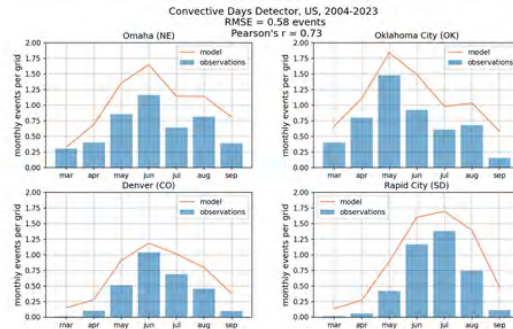


Figure 2: Validation of the CDD model in four of the most populated cities of Central US

Implications for critical sectors

Accurate prediction of hail size and timely forecasts are crucial for mitigating economic impacts and refining risk assessments. In 2023, the insurance industry faced \$60Bn in losses from severe convective storms – almost double from 2022.⁵ Reliable forecasts of hailstorm severity enable insurers to evaluate risks more effectively and tailor policies accordingly.

Future directions

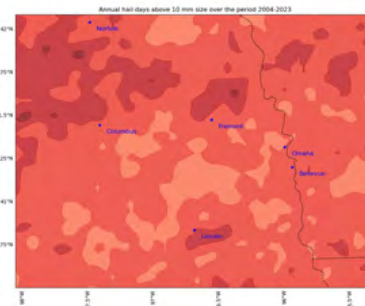


Figure 3: WRF model output showing annual hail days above 10 mm size for the period 2004-2023 in East Nebraska (US)

We are refining the WRF model to enhance its accuracy in predicting hail size and severity. By optimizing model configurations and incorporating advanced statistical techniques, we aim to improve hailstorm impact predictions. Our research incorporates advanced statistical techniques and comprehensive data analysis.

Collaboration with insurance companies, who possess valuable data on hailstorm damages, will strengthen our models and ensure findings are actionable and relevant. Our ultimate goal is to provide innovative, data-driven solutions that help communities, industries, and policymakers better prepare for and respond to the growing threat of hailstorms in a changing climate.

1. T. Rigo and C. Farnell, "A summary of hail events during the summer of 2022 in Catalonia: A comparison with the period of 2013–2021," *Remote Sensing*, vol. 15, 2 2023.
2. J. Allen, I. Giammanco, M. Kumjian, H. J. Punge, Q. Zhang, P. Groenemeijer, M. Kunz, and K. Ortega, "Understanding hail in the earth system," *Reviews of Geophysics*, vol. In Press, 03 2020.
3. T. Pućik, C. Castellano, P. Groenemeijer, T. Kuřhne, A. T. R'adler, B. Antonescu, and E. Faust, "Large hail incidence and its economic and societal impacts across Europe," *Monthly Weather Review*, vol. 147, pp. 3901–3916, 2019.
4. S. Elmisaoui, I. Kissami, and J.-M. Ghidaglia, "High-performance computing to accelerate large-scale computational fluid dynamics simulations: A comprehensive study," in *International Conference on Advanced Intelligent Systems for Sustainable Development (AI2SD'2023)* (M. Ezziyani, J. Kacprzyk, and V. E. Balas, eds.), (Cham), pp. 352–360, Springer Nature Switzerland, 2024.
5. A. Carrns, "Insurers report rising hail damage claims," *The New York Times*, 2024. Last accessed: 2024-08-08.

When it rains, it pours: The growing impact of extreme weather on the UK



Author

James Carruthers

Institution

Newcastle University, United Kingdom

Biography

James is a climate scientist at Newcastle University specializing in the physical and socio-economic dimensions of climate change. He is pursuing a PhD in Climate Science. His research focuses on the drivers behind changes in precipitation and flooding in the UK, in collaboration with Willis Towers Watson (WTW), a leading risk and reinsurance firm. James's work aims to differentiate between natural variability and the impact of climate change on extreme weather events, providing critical insights for catastrophe modeling and risk management in the (re)insurance sector.

He holds an MSc with Distinction in Environment and Development from the London School of Economics and a First-Class Honors BSc in Geography from the University of Sheffield. Before his PhD, James worked at the Environment Agency, gaining valuable knowledge and experience in research methodologies and flood risk management.

Title of thesis

Assessing changes to seasonal winter rainfall in the UK from climate change and natural variability

Contact

j.carruthers2(at)newcastle.ac.uk

The UK's wettest 18 months on record have highlighted a worrying trend of increasingly severe winters driven by natural variability and climate change. As storms intensify and flood risks rise, new research reveals that traditional climate models may underestimate the true scale of future rainfall.

In the UK, we often say, "Rain, rain, go away, come again another day!" Unfortunately, the weather doesn't always heed our pleas. From October 2022 to March 2024, the UK experienced its wettest 18 months on record. This was driven by powerful jet stream episodes across the North Atlantic, which brought a relentless series of storms and heavy rainfall.

The result? Devastating floods from storms like Babet, Gerrit and Henk, wreaked havoc, shattering windows, damaging vehicles, and inundating fields, costing millions of euros in losses and causing widespread disruption. This period follows a pattern of increasingly severe winters, similar to those of 2013/2014, 2015/2016 and 2019/2020, costing £1.3, £1.6, and £0.3Bn respectively, which collectively caused over £3Bn (€3.5Bn euro) in damages.

These extreme events result from a combination of natural variability and long-term climate change. However, disentangling the contribution of each factor is challenging. Detecting the influence of climate change on rainfall patterns is particularly difficult due to the strong influence of natural variability and the relatively short historical records available. Nonetheless, understanding these changes is essential, as it allows us to assess current risks and validate future climate projections.

It's already wetter than expected

Our research aimed to isolate the effects of natural variability on UK winter rainfall from 1900 to 2024. Using 30 weather patterns identified by the Met Office, which categorize daily sea level pressure into the most common synoptic conditions over the UK, we developed a model trained on pre-1980 data – before significant human-induced warming – to predict monthly winter rainfall based on these weather patterns. This model explains approximately 70% of winter rainfall variability.

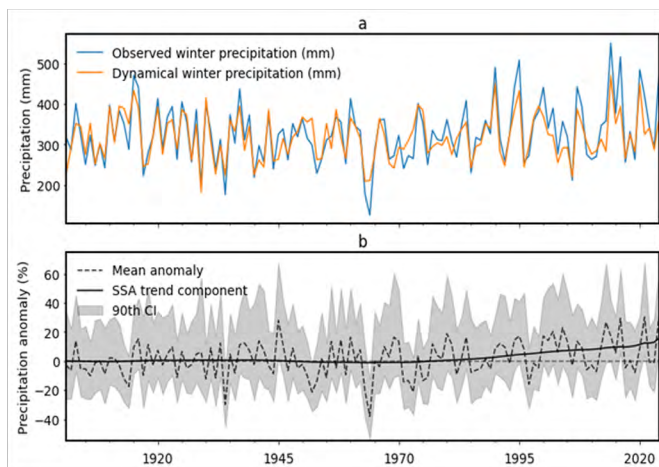


Figure 1: (a) Observed and modelled (dynamical) winter mean rainfall in the UK and (b) percentage difference between observed and modeled rainfall (anomaly), with a trend line. Shaded areas indicate 90th confidence intervals for the rainfall anomaly.

Since our model is based on pre-warming data, we can assess the impact of climate change on winter rainfall by calculating the difference between the observed and modelled rainfall. We identified a clear upward trend since 1980, increasing by about 6.8% per degree of warming, in line with the Clausius-Clapeyron scaling, which describes how atmospheric water content rises with temperature. Our findings indicate that recent winters – such as those of 2013/2014, 2015/2016, 2020/2021 and 2023/2024 – experienced rainfall that would have been extremely unlikely (less than a 5% chance) before 1980.

Climate models fall short

This research is unique because it diverges from the typical approach of using large ensembles of climate models to detect climate change signals. Recent studies suggest that these models may underestimate the strength of such signals, making it challenging to validate findings. By leveraging observed variability, our method offers an alternative way to detect climate change impacts, providing insights that could improve multi-decadal future projections.

Applying our methodology to state-of-the-art climate model projections for the UK, we discovered that these models significantly underestimate the rate at which rainfall increases with temperature. Higher-resolution models achieve more realistic scaling but still fall short of the observed scaling rate.

This discrepancy is concerning because it suggests that climate models predict that natural variability will dominate rainfall changes rather than climate change might not accurately capture the future intensification of rainfall, which could mean that future wet periods may be even more than current models predict.

Implications for the risk industry

Understanding these changing patterns is crucial for the (re)insurance sector, as winter storms are Europe's main loss drivers. In the UK, the sequences of storms in a single season often led to catastrophic flooding. The associated risks also evolve as these patterns change in frequency and intensity. Insurers need to understand not just the average risk but also the variability and potential worst-case scenarios. This knowledge is crucial for risk management, pricing and developing strategies to mitigate losses from extreme weather events.

While we may wish for "rain, rain, go away," it's clear that in our changing climate, we must prepare for it to stay and intensify.

On sliding ground: Urban sprawl and increased flood risk are driving slow-moving landslide exposure



Author

Joaquin Vicente Ferrer

Institution

University of Potsdam, Germany

Potsdam Institute of Climate Impact Research, Germany

Biography

Joaquin is a doctoral researcher in the NatRiskChange doctoral training group with the Natural Hazards working group at the University of Potsdam and a guest researcher in the Complexity Science department at the Potsdam Institute for Climate Impact Research. He holds a background in civil engineering and earned his bachelor's degree from the University of the Philippines Diliman. Joaquin specialized in coastal engineering and storm surge modeling for a year at Osaka University, Japan. He has a unique academic portfolio and completed the Erasmus Mundus Flood Risk Management Master Program, earning three master's degrees from TU Dresden (Germany), IHE Delft (Netherlands), and UPC BarcelonaTech (Spain).

Currently awaiting the defense of his dissertation for a Dr. rer. nat. in Natural Hazards, Joaquin's research focuses on global hazards and exposure to large landslides. He has compiled the most extensive database of landslide inventory data, integrating Earth Observation data to explore uncertainties.

Title of thesis

Human settlement pressure drives slow-moving landslide exposure

Contact

ferrer(at)uni-potsdam.de

Entire towns and villages could be unknowingly situated on slow-moving landslides, yet a comprehensive global overview of this risk has been elusive. Research shows that one in ten landslides could be inhabited and driven by urban expansion and flood exposure.

Annually, landslides take approximately [4,500 lives](#) and cause economic damages of around [\\$20Bn globally](#). [Urban sprawl into hillier areas](#), combined with more intense rainfall due to the climate crisis, is increasing the frequency of landslides and heightening the landslide risk for [39Mn people worldwide](#).

The [2022 Intergovernmental Panel on Climate Change \(IPCC\) report](#) warns that the oncoming climate disaster will elevate both flood and landslide risks for mountain communities. In areas of steep terrain, entire communities can be perched precariously on slow-moving landslides spanning at least 0.1 square kilometers (Figure 1).

These landslides can move at rates ranging from millimeters to meters per year, sliding along failure planes tens to hundreds of meters below the surface. When they accelerate and collapse, the consequences can be catastrophic, demolishing entire villages in minutes.

Despite this slow-moving landslides are often overlooked in risk assessments of populations exposed to landslide risk. Our research provides the first global evaluation of exposure to these landslides in regions identified by the IPCC as facing heightened future disaster risk.¹

Human settlements on slow-moving landslides

We compiled a new database of 7,764 large, slow-moving landslides across IPCC regions (Figure 2). Using [high-resolution data](#), we found that [563 of these landslides host human settlements](#), impacting hundreds of thousands. East

1. Ferrer, J. V., Samprogna Mohor, G., Dewitte, O., Pánek, T., Reyes-Carmona, C., Handwerger, A. L., et al. (2024). [Human settlement pressure drives slow-moving landslide exposure](#). *Earth's Future*, 12, e2024EF004830

Asia, the Mediterranean and Western Central Europe have the highest concentration of built-up areas on slow-moving landslides, with the densest settlements in [La Paz, Bolivia](#), and [Bukavu in the Democratic Republic of Congo](#).

Our study further explored the influence of urbanization, steepness and flooding on landslide exposure using advanced statistical modeling within a Bayesian framework. This enabled us to draw statistical inferences from regional models and capture large uncertainties in regions with small sample sizes.

We discovered that urbanization often forces communities onto unstable slopes, especially where expansion options are limited. For example, the [Pampahasi landslide](#) in La Paz, Bolivia, collapsed in February 2011, affecting 1.5 square kilometers, destroying 1,000 homes and displacing 6,000 people (Figure 1b). [Despite ongoing landslide activity](#), more than half of this area was repopulated by 2022.

Such areas as La Paz typically attract poorer communities with limited affordable housing options, forcing them to settle in vulnerable locations. These informal [settlements are often constructed with inadequate materials and lack proper land-use planning](#).

Additionally, we found that communities are more likely to settle on slow-moving landslides in regions with high flood risk. Restrictive building regulations in flood-prone areas [can drive expansion onto landslide-prone hillslopes](#). For instance, in Italy's Arno River basin, [€7Bn in assets are at risk of slow-moving landslides](#) as communities shift away from flood zones.

Heightened risk due to uncertainty

Growing populations in mountainous regions face a high risk from landslides and floods, which are expected to intensify under climate change. [Divergent projections for these populations range from tens to hundreds of millions](#) by 2100.

Although the climatic triggers for slow-moving landslides remain uncertain, [shifts between extremely dry and wet seasons](#) are known to accelerate their motion and exacerbate [flood risk](#). If protective measures fail to keep pace with extreme flooding, [communities could be pushed](#) uphill onto dangerous landslide-prone slopes.

Our findings provide a foundation for future assessments of landslide exposure, emphasizing the need for more comprehensive mapping and monitoring, particularly in under-researched regions like the Hindu-Kush Himalayas, East African Rift, Northeast Africa and South American Andes. Countries in these areas require more significant investment in research to identify and monitor thousands of landslides, enabling more accurate risk estimates and understanding of their drivers.

We call for [a coordinated approach to climate change adaptation and disaster risk reduction policies in mountain regions](#) to prevent flood mitigation from inadvertently increasing landslide exposure.

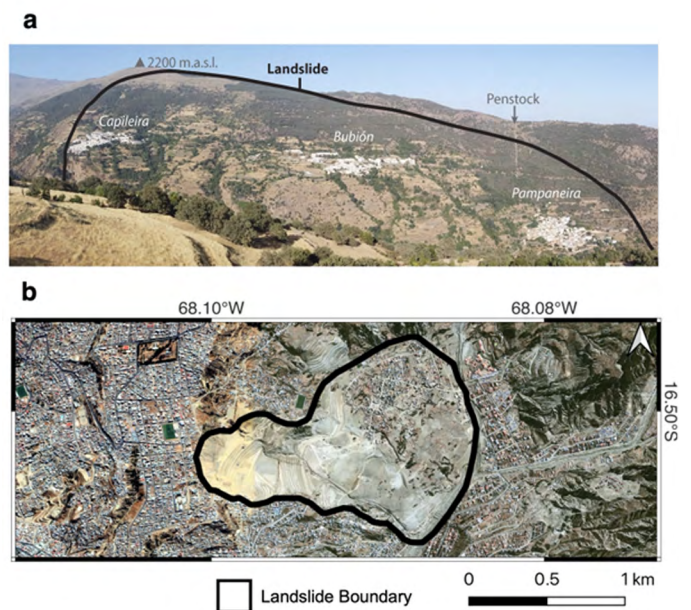


Figure 1: Human settlements on slow-moving landslides; (a) Villages in the Poqueira Valley, Spain, situated on slow-moving landslides. (b) The Pampahasi landslide embedded in La Paz, Bolivia. Figure adapted from Ferrer et al. (2024).

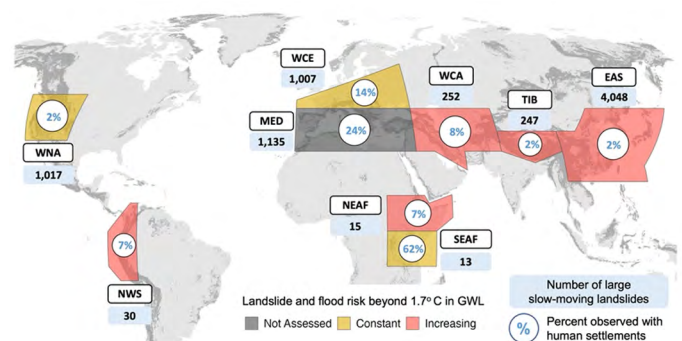


Figure 2: Global distribution of landslides and their occupation status as of 2015. IPCC reference regions include East Asia (EAS), the Mediterranean (MED), Northeast Africa (NEAF), North-Western South America (NWS), Southeast Africa (SEAF), the Tibetan Plateau (TIB), Central Asia (WCA), Western Central Europe (WCE) and Western North America (WNA). Landslide and flood risk assessments beyond 1.7°C in global warming level (GWL) were adapted from the 2022 IPCC report on mountains. Figure adapted from Ferrer et al. (2024).

The chances and limits of on-farm crop diversification to cope with drought risk



Author

Jonas Schmitt

Institution

Eidgenössische Technische Hochschule (ETH Zurich), Switzerland

Biography

Jonas is an Agricultural Economics and Policy researcher at ETH Zürich, specializing in weather risk management. With over four years of experience at the Thuenen-Institute and the German Ministry of Agriculture, he has developed expertise in assessing weather risks and evaluating both on-farm and off-farm risk management strategies.

His work offers valuable insights into the effectiveness of these strategies under extreme weather conditions, particularly drought. Jonas has closely followed the political discourse on governmental support for weather risk management and its implications. His recent research explores the need for innovative insurance solutions when traditional on-farm practices, such as crop diversification, are insufficient.

Title of thesis

Drought risk management in agriculture: A copula perspective on crop diversification

Contact

joschmitt(at)ethz.ch

Drought events are a leading cause of substantial crop yield losses, posing significant risks to food security and farmers' incomes. One commonly employed risk management strategy to combat these drought impacts is on-farm crop diversification, which involves growing multiple crops simultaneously during a cropping season.

The effectiveness of crop diversification varies with drought severity, crop composition and environmental circumstances like soil quality. Our study aims to address this knowledge gap by evaluating simultaneous farm-level yield losses of different cash crops in German agriculture – including winter wheat, winter barley, winter rapeseed, sugar beet and grain maize – across different drought severity levels and different regions. We analyzed 249,756 regionally pooled farm-level crop-yield pairs from 1995 to 2019 to determine how crop diversification contributes to drought risk management.

Impact of extreme weather on agriculture

Extreme weather events, particularly droughts, frequently result in significant yield reductions, impacting food security and farmers' incomes. For instance, droughts in 2003 and 2018 caused yield losses exceeding 20% for a broad range of crops in numerous European regions (Beillouin et al., 2020; Ciais et al., 2005; Schmitt et al., 2022; Webber et al., 2020). With the climate crisis exacerbating drought risk (Grillakis, 2019; Brás et al., 2021), the threat to food production and the economic viability of farms is intensifying, presenting significant implications for industry and policy.

Diversifying cropping patterns during planting seasons is a crucial strategy to manage drought risk and diverse crop rotations can stabilize food production and farm incomes. However, the efficacy of crop diversification under extreme drought conditions and the most promising crop combinations are not well understood. This information is crucial for farmers and policymakers to make informed decisions. This study quantifies the risk-reducing potential of crop diversification at the farm level, particularly in extreme drought-related yield shocks.

Variability in the effectiveness of crop diversification

Our findings reveal that while crop diversification can mitigate drought risk, its effectiveness is highly dependent on crop combinations, regional growing conditions and drought severity. For example, under severe drought (a one-in-20 years event), 26.4% of farms in eastern Germany experienced simultaneous yield losses of $\leq -20\%$ in winter wheat and winter barley (see Figure 1). In comparison, 19.1% of these farms experience similar winter wheat and sugar beet losses of $\leq -20\%$ during severe drought. The risks were considerably lower in western Germany, where only 3.6% of farms experienced simultaneous yield losses of $\leq -20\%$ in winter wheat and winter barley, and 1.6% in the winter wheat and sugar beet combination (see Figure 2).

Supporting farmers' weather risk management

As a result, farmers can more effectively mitigate risk through diversification by growing crops with different phenological needs and water requirements throughout the year. However, since crop diversification as a traditional on-farm risk management instrument is ineffective on many farms when drought becomes severe, off-farm risk management measures such as insurance

should be considered as a complementary strategy. Future research should explore how the portfolio effects of crop diversification can be leveraged in agricultural insurance products to offer more robust protection against weather extremes.

Our analysis has important policy implications. Policymakers should use these insights to create a supportive framework enabling farmers to implement crop diversification most effectively. For example, encouraging the cultivation of crops with varying phenological requirements (different growth stages) and water needs throughout the year can enhance the resilience of agricultural systems to weather extremes.

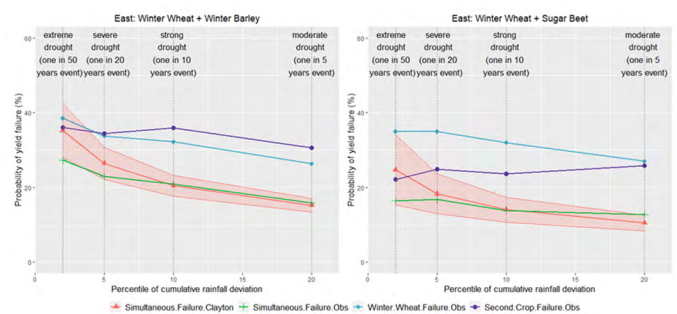


Figure 1: Sub sample of eastern Germany – probabilities of simultaneous yield losses under different drought levels, based on nested Clayton copula estimates compared to single-crop observations.

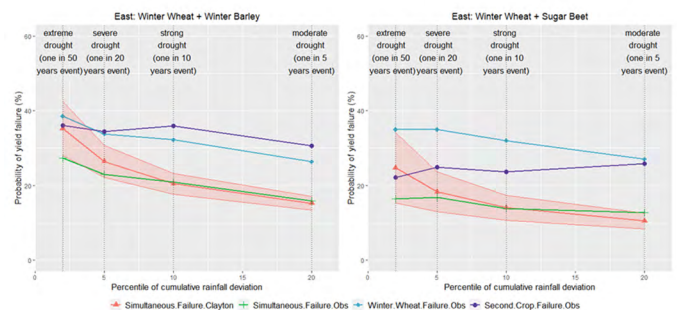


Figure 2: Sub-sample of western Germany – probabilities of simultaneous yield losses under different drought levels, based on the nested Clayton copula estimates compared to single-crop observations.

1. Beillouin, D., Schauberger, B., Bastos, A., Ciais, P., & Makowski, D. (2020). *Impact of extreme weather conditions on European crop production in 2018*. *Philosophical Transactions of the Royal Society B*, 375(1810), 20190510.
2. Brás, T. A., Seixas, J., Carvalhais, N., & Jägermeyr, J. (2021). *Severity of drought and heatwave crop losses tripled over the last five decades in Europe*. *Environmental Research Letters*, 16(6), 065012.
3. Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., ... & Valentini, R. (2005). *Europe-wide reduction in primary productivity caused by the heat and drought in 2003*. *Nature*, 437(7058), 529-533. Cui, X. (2020). *Beyond yield response: weather shocks and crop abandonment*. *Journal of the Association of Environmental and Resource Economists*, 7(5), 901-932.
4. Grillakis, M. G. (2019). *Increase in severe and extreme soil moisture droughts for Europe under climate change*. *Science of The Total Environment*, 660, 1245-1255.
5. Schmitt, J., Offermann, F., Söder, M., Frühauf, C., & Finger, R. (2022). *Extreme weather events cause significant crop yield losses at the farm level in German agriculture*. *Food Policy*, 112, 102359.
6. Webber, H., Lischeid, G., Sommer, M., Finger, R., Nendel, C., Gaiser, T., & Ewert, F. (2020). *No perfect storm for crop yield failure in Germany*. *Environmental Research Letters*, 15(10), 104012.

Predicting the unpredictable



Author

Joseph W Lockwood

Institution

Columbia University, United States

Biography

Joseph is a postdoctoral scientist at Columbia University's Data Science Institute, specializing in machine learning and generative AI for energy modeling, physics and health impacts. He holds a PhD and MA in Applied Physics with Computational Science & Engineering from Princeton University, an MSc in Data Science with Computer Science from the University of Sunderland and an MSc in Atmospheric & Oceanic Science from McGill University. With a BSc in Physics (Geophysics) from the University of Southampton, Joseph's extensive background spans data science, atmospheric science and computational physics.

His research focuses on leveraging advanced machine learning techniques to enhance the accuracy and resolution of tropical cyclone predictions, addressing real-world challenges in catastrophe risk modeling. Previously, he developed physical models for rainfall, tropical cyclones and storm surges at Reask in London. Joseph aims to provide critical insights and tools for risk management and disaster preparedness.

Title of thesis

Improving Extreme Weather Modeling with Machine Learning: An Application to Tropical Cyclone Wind Fields

Contact

jl6895(at)columbia.edu

Despite advancements in climate modeling, existing models struggle to capture the intricate dynamics of tropical cyclones.

Tropical cyclones (TCs) are among the most devastating natural phenomena, causing extreme wind speeds, floods, loss of life and substantial economic damage globally. Accurate prediction of TC hazards is essential for effective risk and energy modeling but remains one of the most challenging tasks in weather forecasting. Short-duration deviations from average atmospheric states and the complex dynamics within a TC's inner and outer cores make precise modeling difficult. While advances in climate modeling and numerical weather prediction (NWP) have improved TC simulations, existing models still face significant limitations.

One of the challenges in simulating TCs lies in the resolution of current models. Most climate and weather models, including atmospheric reanalysis products, use spatial resolutions ranging from 0.25° to 1°. While these resolutions are sufficient for large-scale atmospheric dynamics, they struggle to capture the intricate inner-core dynamics of TCs. This leads to a systematic underestimation of TC intensity, especially for extreme events.

Moreover, increasing the resolution of these models requires considerable computational resources, making high-resolution simulations costly and limiting the number of ensemble forecasts available. Ensemble forecasts are critical for quantifying uncertainty and improving forecast skills.

The promise of machine learning for weather modeling

Recent advancements in machine learning (ML) have opened new avenues for improving weather modeling and forecasting. Deep learning models like Aurora, GraphCast and Pangu-Weather have demonstrated potential by providing faster, scalable and often more accurate forecasts than traditional NWP models.

These models use datasets and advanced computer vision architectures to accelerate weather modeling, offering scalability and adaptability. However, predicting extreme weather like TCs remains a challenge. ML models often struggle with coarse spatial resolution, limited scale awareness and a tendency to blur fine-scale structures. This limitation is particularly problematic when predicting TC intensity and rapid intensification.

Super-resolution techniques in ML have emerged as powerful tools to enhance spatial resolution and improve the accuracy of extreme weather event predictions. These methods are now being adapted for weather downscaling. Techniques like transformers, generative adversarial networks (GANs) and denoising diffusion probabilistic models (DDPMs) can generate high-resolution data from low-resolution inputs, surpassing traditional interpolation methods.

Leveraging diffusion models for TC downscaling

Super-resolution techniques have transformed the way we model extreme weather. My research introduces a deep-learning framework that combines debiasing neural networks with DDPMs to enhance the prediction of high-resolution TC wind fields. This addresses the limitations of current models by directly tackling the resolution gap and enabling more accurate intensity predictions.

I applied this to ERA5 reanalysis data in my research, increasing the resolution from 0.25° to 0.05° (~25 km to 5 km) using advanced diffusion models. The model also improved extreme wind speed predictions and generated high-resolution ensemble forecasts that capture the fine-scale structures of TC wind fields. This enables more accurate modeling of TC intensity and radial profiles, with DDPMs providing probabilistic estimates that account for the inherent uncertainties in TC prediction. By leveraging the probabilistic nature of DDPMs, the model generates ensemble forecasts that provide a robust understanding of uncertainty.

The framework has demonstrated the ability to reconstruct high-resolution wind fields from past events and forecast future wind fields, even during periods without satellite observations. This is essential for improving the accuracy of TC modeling and risk management, particularly in correcting wind intensity underestimations from low-resolution models such as CMIP6, GraphCast and Pangu-Weather. By enhancing the detail and accuracy of TC wind field predictions, our approach provides a valuable tool for better understanding and mitigating TC-related risks.

Future directions and broader implications

My research advances the state-of-the-art in TC prediction and opens new avenues for applying ML models to other climate challenges. The cascading deep learning framework can be adapted to different extreme weather phenomena, such as heatwaves, flooding and storm surges, providing a versatile tool for improving disaster resilience in a changing climate.

I plan to refine this by incorporating additional physical constraints to ensure that the enhanced wind fields align with atmospheric dynamics. As we continue to push the boundaries of ML in weather prediction, the potential to mitigate the impacts of extreme weather events becomes increasingly within reach.

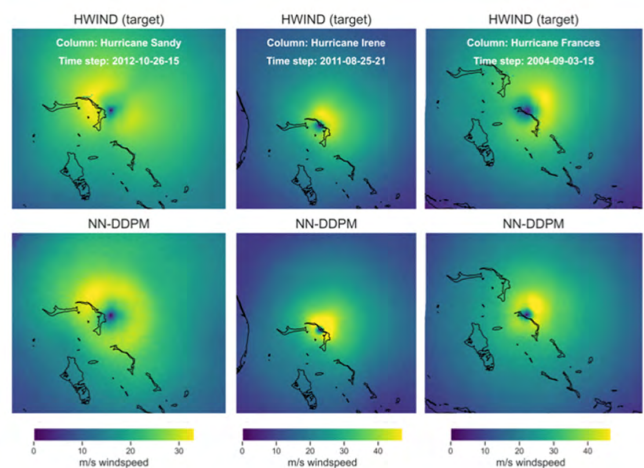


Figure 1: Shows the target high-resolution wind data (0.05 degree), and the prediction of the super-resolution diffusion model. The input to the diffusion model is ERA5 reanalysis data with a resolution of 0.25 degree. The figure shows a comparison between the target observations (top row) and super-resolution model output (bottom row). The input to the bottom is coarse-resolution ERA5 data at 0.25-degree resolution, the model output is 0.05 degrees.

Winds of change in tropical cyclone modeling



Author

Simona Meiler

Institution

Eidgenössische Technische Hochschule Zürich (ETH Zurich), Switzerland

Biography

Simona completed her PhD at the Institute for Environmental Decisions, ETH Zurich. She specializes in weather and climate risk modeling, focusing on tropical cyclone (TC) risk and impact assessment. In her first PhD project, she led a global intercomparison study, collaborating with top academic TC modelers to evaluate model performance. Her recent research delves into the uncertainties and sensitivities of TC risk quantification, forming the foundation of her latest paper.

Simona's work has been recognized at prestigious academic conferences like the Symposium on Hurricane Risk in a Changing Climate and industry events like the Oasis Insight Conference, presenting her as a leading early-career scientist. Her expertise bridges the gap between academic research and practical industry applications, contributing valuable insights to the field of climate risk science.

Title of thesis

Unraveling unknowns in tropical cyclone risk assessment

Contact

simona.meiler(at)usys.ethz.ch

Future tropical cyclone risks will depend on the complex interplay of climate change and socioeconomic development, both introducing substantial uncertainties.

Tropical cyclones (TCs) have devastating impacts on many tropical and subtropical coastal regions. For example, Hurricane Ian (2022) wreaked havoc in western Cuba with sustained winds over 200 km/h, leaving the island without power and prompting the evacuation of over 38,000 residents.

Given the consequences reliable TC risk assessments are crucial to support risk mitigation efforts and enhance societal resilience. However, these assessments are complicated by the limited availability of reliable TC records. Synthetic TC models have been developed to address this, but until recently, they have not been directly compared for risk and loss estimation in catastrophe models.

My work introduced the first intercomparison of four academically available, global-scale synthetic TC datasets, evaluating their performance for risk and impact assessment.¹ This study guides users in selecting suitable TC models and provides the industry with a benchmark for evaluating their TC models.

Future TC risk assessments require additional model input representing future climate and socioeconomic systems, each introducing distinct uncertainties. Therefore, I systematically quantify uncertainties and sensitivities in future TC risk projections, considering uncertainties in all risk model components: hazard, exposure and vulnerability.

Measuring the unknowns

Uncertainty in TC risk assessments stems from random variability (aleatory uncertainty), limited knowledge (epistemic uncertainty) and normative choices in model design. Different methods for uncertainty and sensitivity analysis have been proposed. Uncertainty analysis quantifies the overall uncertainty, while sensitivity analysis identifies the contributions of different input factors to that uncertainty.

I apply an uncertainty and sensitivity quantification module² integrated into the risk modeling platform CLIMADA,³ using a Quasi-Monte Carlo scheme to repeat risk calculations over 20,000 times. This approach allows me to explore the uncertainty in risk model components such as different future climate scenarios, socioeconomic pathways and vulnerability functions. A schematic overview conducted by Meiler et al. (2024)⁴ is shown in Figure 1.

It's complicated

My research shows that while climate change and socioeconomic development influence TC risk changes in the future, socioeconomic factors are the primary drivers of median risk increases. By 2050, median TC risk will increase by 1-5% across all TC models and global regions, which may be considered moderate in some contexts. However, maximum risk increases by 2100 range from 10-400%, depending on the hazard model choice.

Since no hazard model or socioeconomic scenario can be excluded, this points to a potentially significant increase in risk.⁴ This insight would have been overlooked without a thorough and systematic uncertainty analysis covering a wide range of possible futures.

The dominant source of uncertainty varies depending on the specific risk model setup. Sensitivity analysis reveals that socioeconomic factors, specifically the GDP-scaling factor derived from the Shared Socioeconomic Pathways (SSPs), are often the most significant source of uncertainty.⁴ In one TC model, however, the dominant source of uncertainty is the choice of global climate model (GCM) used in downscaling TC events.⁵ These findings underscore the need to evaluate such results within the context of the study setup, as different models and assumptions can lead to vastly different conclusions.

Turning uncertainty into insight

My work provides a framework for analyzing sources of uncertainty in TC risk assessments, enhancing the transparency and value of the results. This enables model developers to focus on key inputs that reduce output uncertainty and equips decision-makers with a more representative range of future outcomes.

My research advances global TC risk assessments, by offering a robust basis for decision-making and model refinement, yielding enhanced and actionable insights. Finally, the concepts and methodologies developed are not limited to TC risk assessment but can be broadly applied to various climate risks, enhancing resilience across multiple hazards.

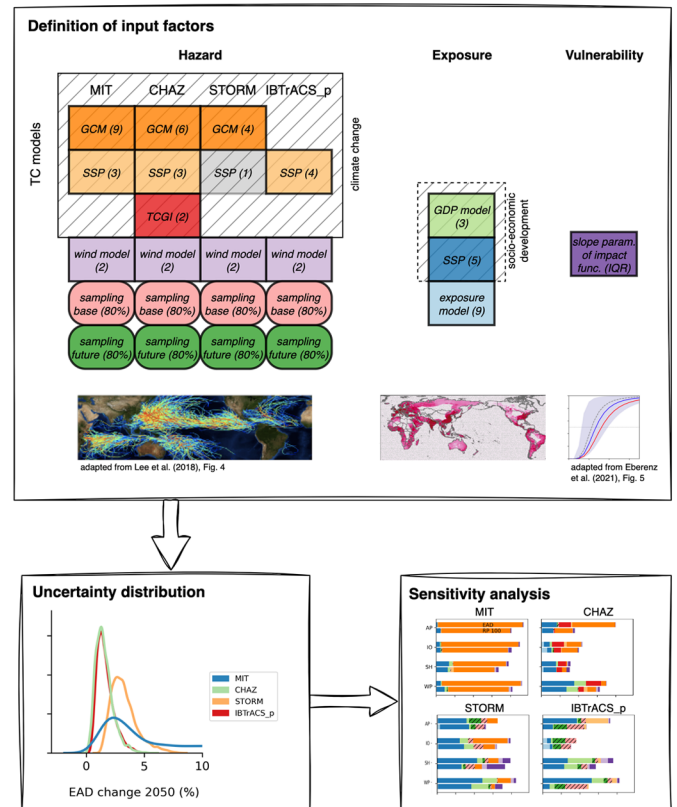


Figure 1: Schematic overview of uncertainty and sensitivity analysis. The definition of input factors shows which risk model components are varied (top box). Input factors related to the hazard are defined separately for each TC model (MIT, CHAZ, STORM, IBTrACS_p). TC model-related input factors are labeled as such. Climate change modulates the hazard, socio-economic development and exposure; input factors affected by either are hatched. Input factors representing primarily aleatory uncertainty are shown in rounded boxes; epistemic uncertainty in square boxes. The information in brackets indicates the parameter range (discrete or continuous) from which the input factors are sampled. Note that STORM is run only for SSP5-8.5, so SSP is present in the STORM model structure but not sampled in the analysis. The respective box is grey and marked (1).

An illustration at the bottom of the box depicts the three risk model components. The risk calculation is repeated (>20 000) times for all combinations of input factors, yielding an uncertainty distribution for the risk change estimates (here change in expected annual damage (EAD)) for each TC model setup (lower left box). Sensitivity indices are calculated from these distributions (lower right box), both illustrated with output from the actual analyses in this study.

1. Meiler, S., Vogt, T., Bloemendaal, N., Ciullo, A., Lee, C.-Y., Camargo, S. J., Emanuel, K., & Bresch, D. N. (2022). *Intercomparison of regional loss estimates from global synthetic tropical cyclone models*. *Nature Communications*, 13(1), 6156.
2. Kropf, C. M., Ciullo, A., Otth, L., Meiler, S., Rana, A., Schmid, E., McCaughey, J. W., & Bresch, D. N. (2022). *Uncertainty and sensitivity analysis for probabilistic weather and climate-risk modelling: An implementation in CLIMADA v.3.1.0*. *Geoscientific Model Development*, 15(18), 7177–7201.
3. Aznar-Siguan, G., & Bresch, D. N. (2019). *CLIMADA v1: A global weather and climate risk assessment platform*. *Geoscientific Model Development*, 12(7), 3085–3097.
4. Meiler, S., Kropf, C. M., McCaughey, J. W., Lee, C.-Y., Camargo, S. J., Sobel, A. H., Bloemendaal, N., Emanuel, K., & Bresch, D. N. (2024). *Navigating and attributing uncertainty of future tropical cyclone risk estimates*.
5. Meiler, S., Ciullo, A., Kropf, C. M., Emanuel, K., & Bresch, D. N. (2023). *Uncertainties and sensitivities in the quantification of future tropical cyclone risk*. *Communications Earth & Environment*, 4(1), 1–10.

Riding Out the Storm: Proactive Urban Planning for Catastrophic Flood Resilience



Author

Supriya Krishnan

Institution

Delft University of Technology,
The Netherlands

Biography

Supriya is an urban planner and researcher at the Faculty of Technology, Policy, and Management (Resilience Lab) at Delft University of Technology in the Netherlands. Her work focuses on long-term urban planning in the face of climate uncertainty. Supriya's doctoral research at TU Delft explored how cities integrate medium- and long-term climate commitments into actionable strategies within their master plans, particularly emphasizing the gap between data-rich and data-scarce environments.

She made significant contributions to the field by developing (a) a theoretical foundation for understanding the temporal dynamics of "connected and moving" cities, which are increasingly vulnerable to catastrophic risks. (b) a conceptual framework for embedding resilience within urban planning frameworks, and (c) a blended approach to designing contextualized long-term urban scenarios, utilizing computational models, narrative scenarios, practitioner insights, and localized knowledge.

Title of thesis

Riding Out the Storm: Proactive Urban Planning for Catastrophic Flood Resilience

Contact

s.krishnan(at)tudelft.nl

Western Europe has experienced catastrophic floods that far exceed official hazard map predictions. In 2021, rivers burst their banks, dams and dikes were pushed to the brink and entire regions were overwhelmed.

Engineered flood defenses – dikes, dams, and seawalls – are often seen as silver bullets for managing flood.¹ The [Netherlands Delta Programme](#), a global leader in water management, aims to reinforce over 1,500 kilometers of dikes to establish a 'baseline' level of protection.² However, recent disasters have exposed even the best defenses, underscoring the need for a more comprehensive approach that includes both planning and insurance solutions for extreme weather.^{3,4,5}

While engineered structures are vital, damage to these defenses can exacerbate risks from extreme rainfall and storm surges. Regions protected by dikes rely heavily on pumping capacity, but a [five-meter sea level rise would require 60 times the pumping power of the Netherlands' largest facility](#). Moreover, these defenses can create a false sense of security – commonly known as the levee effect⁶ – encouraging risky development in vulnerable areas. With climate conditions worsening, traditional methods, like raising dikes, are becoming less viable, necessitating innovative approaches.⁷

The insurance industry is increasingly stretched as once-rare catastrophic events grow more frequent. For instance, efforts to expand flood insurance in the Netherlands often hit a wall due to the high premiums required to offset such risks. Insurers frequently rely on short-term fixes, while regulations impose measures to mitigate market fallout from catastrophic events. A similar mindset is also seen in urban planning, where low-probability, high-impact risks are often overshadowed by more immediate development priorities.^{8,9}

Planning for the worst

To build long-term resilience, urban planners and insurers must collaborate to think outside the box and promote preventive and adaptive measures, including relocating flood-prone areas and developing risk-adjusted insurance products. This study explores how scenario-based planning can guide resilient urban growth in the face of catastrophic flooding, advocating for strategies beyond traditional risk management.

Managing extreme risks requires a multi-pronged approach: (1) risk-informed urban planning, (2) targeted upgrades of flood defenses and (3) comprehensive insurance policies. These elements must work hand in glove to mitigate immediate threats while reducing long-term vulnerabilities. Planning with worst-case

scenarios in mind is crucial, especially when significant shifts – such as relocating settlements, reinforcing dikes and integrating flood management into broader policy goals – are needed. These decisions demand long-term strategic thinking.⁸

Methodology

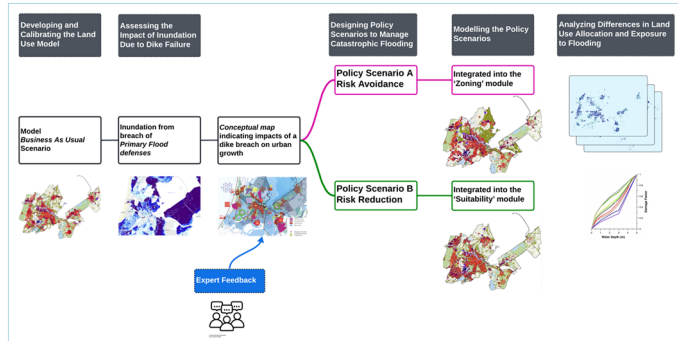


Figure 1: Research Methodology highlighting the development of the land use model, the integration of the flood risk map and the design and modeling of policy scenarios to manage catastrophic flooding from the failure of flood defenses. The methodology includes scenario development, spatial modeling and policy analysis to explore the impacts of different flood management strategies.

This research charts a new course by assessing the spatial impacts of catastrophic flooding on urban regions, focusing on: (a) how different risk management strategies can guide urban growth to mitigate long-term risks, and (b) how policies can adapt to reduce future risk exposure.

We use a mixed-methods approach, blending computational land-use models, expert insights and desk research to evaluate two contrasting policy responses: **Risk Avoidance** and **Risk Minimization**. The study focuses on the Metropolitan Region of Amsterdam. The region relies almost entirely on the IJmuiden pumping complex on the North Sea coast, which is already operating beyond capacity. This dependency poses significant flood risks for the region. (Figure 1).

- **Scenario A (Risk Avoidance): ‘Better Safe Than Sorry’** – Enforces strict regulations to prevent development in flood-prone areas, relying on structural engineering to mitigate risks.
- **Scenario B (Risk Minimization): ‘Walking the Tightrope’** – Balances flood risk with urban growth, incorporating adaptive measures like flexible zoning and green infrastructure to soak up floodwaters.

Navigating the trade-offs

Under each scenario (Figure 2), we analyze urban structure, land-use allocation and risk exposure using the Global Flood Depth Damage Function. Comparing these with a **Business-As-Usual (BAU)** scenario reveals the trade-offs between restrictive risk avoidance and more flexible risk minimization approaches. While restrictive measures may conflict with development goals, more flexible strategies can enhance resilience but require careful management of cumulative risks.

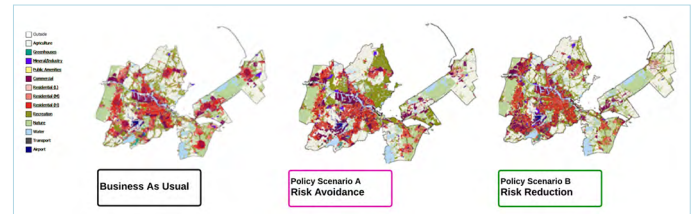


Figure 2: Comparison of urban growth patterns under different policy scenarios for managing catastrophic flooding. It illustrates urban expansion under Scenario A (Risk Avoidance), which steers development away from high-risk areas; Scenario B (Risk Minimization), which balances flood risk and urban growth; and Business As Usual, which assumes growth without targeted flood management interventions.

Our goal is to provide long-term solutions for a future where climate-change-induced extreme flooding is a given. By adopting a precautionary principle and assuming extreme inundation due to flood defense failure, this study encourages a shift from reactive to proactive policymaking.

Implications for the insurance industry

This research underscores the critical need for insurers and urban planners to collaborate in building flood resilience. Shared visualization tools, such as extreme scenario maps, can help both sectors better understand the impact of catastrophic flood risks, consider short- and long-term challenges and adopt strategies that regulate premiums and incentivize resilience-building measures.^{10, 11} This collaborative approach provides a guideline for navigating an increasingly uncertain climate future, ensuring sustainable urban development and more secure, prepared communities.

1. Adam Voiland, Lauren Dauphin 2021. *Deadly Floods Surprise Europe*. NASA Earth Observatory. Accessed: 28 August 2024.
2. IPCC, 2012 – Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.) Available from Cambridge University Press.
3. Ben van Raaij 2021. *Deltakennis is Nederlands exportsucces*. De Volkskrant. Accessed: 28 August 2024).
4. GFZ Helholz Zentrum Potsdam 2024. *Anlässlich der Hochwasserlage in Süddeutschland*. Helmholtz Centre Potsdam – German Research Centre for Geosciences (GFZ). Accessed: 28th August 2024.
5. Thomas Erdbink 2023. *Averting disaster, a broken dike is fixed in the Netherlands*. The New York Times. Accessed: 28 August 2024.
6. Lebel, L. and Sinh, B.T., 2009. Risk reduction or redistribution? Flood management in the Mekong region. *Asian Journal of Environment and Disaster Management*, 1(1).
7. Kiesel, J., Honsel, L.E., Lorenz, M., Gräwe, U. and Vafeidis, A.T., 2023. Raising dikes and managed realignment may be insufficient for maintaining current flood risk along the German Baltic Sea coast. *Communications Earth & Environment*, 4(1), p.433.
8. Krishnan, S., Aydin, N.Y. and Comes, T., 2024. TIMEWISE: Temporal Dynamics for Urban Resilience-theoretical insights and empirical reflections from Amsterdam and Mumbai. *npj Urban Sustainability*, 4(1), p.4.
9. Krishnan, S., Aydin, N.Y. and Comes, T., 2023. RISE-UP: Resilience in urban planning for climate uncertainty-empirical insights and theoretical reflections from case studies in Amsterdam and Mumbai. *Cities*, 141, p.104464.
10. Süddeutsche Zeitung 2024. *When the water recedes, the work begins*. Allianz Re. Accessed: 28 August 2024. Kunreuther, H., 2015. The role of insurance in reducing losses from extreme events: The need for public-private partnerships. *The Geneva Papers on Risk and Insurance-Issues and Practice*, 40, pp.741-762.

Global multi-hazard risk assessment in a changing climate



Author

Zélie Stalhandske

Institution

Eidgenössische Technische Hochschule Zürich (ETH Zürich), Switzerland

Biography

Zélie is a PhD candidate in climate risk assessment at the Group for Weather and Climate Risks at ETH Zürich, Switzerland. Her research models the combined risks of multiple extreme weather events and their impacts on health and infrastructure. Zélie has contributed to the Lancet Countdown on Health and Climate Change and has been actively involved in developing methodologies for multi-hazard risk assessment using the CLIMADA platform. Her work also explores the cascading effects of multi-hazard events, including disruptions to supply chains and critical infrastructure. Her previous internship at MSCI provided her with hands-on experience by working on developing climate risk models for financial services.

Title of thesis

Global Multi-hazard Risk Assessment in a Changing Climate

Contact

zelie.stalhandske(at)usys.ethz.ch

Risk assessments often overlook the interconnected nature of climate-related events, potentially leading to underestimations or inefficient resource allocation. By acknowledging these interdependencies and considering recovery dynamics, we can more effectively manage risk in the face of evolving climate and socioeconomic conditions.

Traditionally, risk assessments have examined individual hazards in isolation, often ignoring the interconnections among climate-related events. This narrow focus can lead to significant underestimations of risk. For example, [strong El Niño events](#) typically increase rainfall and flooding in South America while simultaneously triggering severe droughts and wildfires in Southeast Asia. Portfolio managers with assets in these regions may face unexpected outcomes if they overlook teleconnections.

Ignoring the interconnected nature of hazards can also lead to inefficient resource allocation. For example, separate insurance policies for each hazard can require excessive reserves. Consider maintaining reserves for two different hazards, each with a 1% annual probability (a 100-year return period). It is unlikely that both events would occur in the same year unless driven by the same processes.

Risk models must acknowledge the interdependencies between hazards to avoid underestimations and overestimations.

Beyond temperature: The broader implications of climate change

Our understanding of hazard connections largely relies on historical data, but the climate has diverged from historical norms. Climate change affects more than just average temperatures; it influences a broad range of environmental factors, including the mechanisms driving hazards and their interactions.

For instance, changes in ocean currents and sea surface temperatures can significantly influence the frequency and intensity of tropical cyclones and modify rainfall patterns. While existing climate models may not fully capture these dynamics, they provide valuable insights and are continuously being refined.

Our study¹ focuses on tropical cyclones and river floods – the two most damaging climate-related hazards – to demonstrate how an event-based, probabilistic risk assessment method can be conducted in a changing climate. We have developed a novel approach that samples from single-hazard event loss sets based on the same climate model data. We evaluate the combined risk of these two hazards under scenarios where the global temperature rises by 1°C and 2°C above pre-industrial levels, considering potential damages and recovery dynamics.

A key aspect of our methodology is defining a common time and spatial relevance for hazard impacts. While traditional studies on climate extremes often assess events based on meteorological timescales (days to weeks), we propose evaluating impacts within a calendar year. This approach is more aligned with the decision-making processes of many organizations.

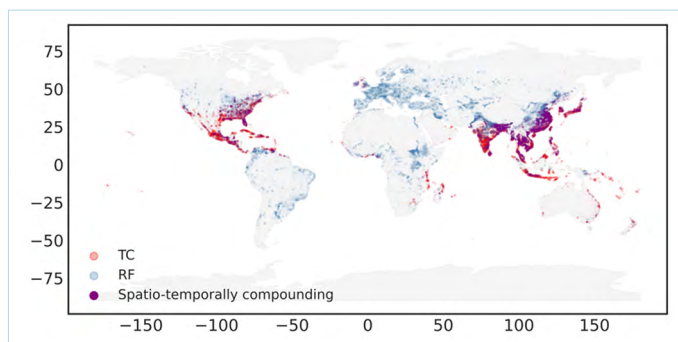


Figure 1: Exposure points affected by tropical cyclones, river floods and their compound on average per year at a 1°C warming level with at least \$1,000 damage on average per year

Our analysis produced global maps (Figure 1) showing where single hazards and their compounding impact populations and the return periods for these events at varying warming levels (Figure 2). The map highlights regions where multi-hazard assessments are most needed. Additionally, we found that accounting for common physical drivers when combining events leads to an overall higher risk.

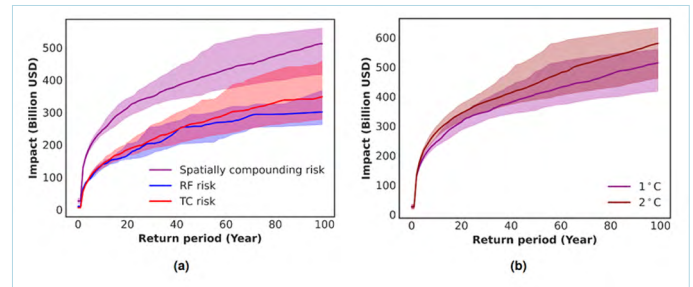


Figure 2: Impact return period curves for river floods, tropical cyclones and their compound risk, illustrating the median and 90th percentile confidence intervals. (a) Shows the contribution of each hazard and the combined risk at 1°C, while (b) shows the combined risk at 1°C and 2°C.

The role of recovery

Recovery is critical when considering a series of events, especially with multiple hazards, as a prior event can influence asset value and vulnerability. Initially, we assume that assets fully recover at the end of each calendar year, implying damages are repaired within the year and that maximum damage cannot exceed the assets' value. We then explore different recovery timelines, up to five years, in a case study. Longer recovery times can be financially beneficial as asset values remain lower for an extended period, but from a societal perspective, prolonged recovery can disrupt functionality and increase vulnerability.

While our study does not directly address how recovery from past events influences vulnerability, this is a crucial area for future research to incorporate into risk assessment models.

Our study significantly contributes to a more holistic approach to risk modelling. We provide a framework to assess the effects of the climate crisis on multi-hazard risk at relevant spatial and temporal scales and to develop multi-hazard storylines. Implemented in the open-source [CLIMADA platform](#), our framework can be applied in numerous case studies and supports a broad range of hazard assessments.

By integrating evolving dependencies among multiple hazards, recovery processes and changing vulnerabilities over time, we enable more effective risk management strategies in an era of shifting socioeconomic and climate conditions.



IMPRINT

Publisher:

Allianz SE Reinsurance
Königinstraße 28
80802 Munich, Germany

Design:

Creative Design Services

Contacts:

Dr. Carolin Pommeranz
carolin.pommeranz@allianz.com

Md Abu Redwan Khan
md-abu-redwan.khan@allianz.com