



**Manchester  
Metropolitan  
University**

---

Feldmeyer, D and Birkmann, J and McMillan, JM and Stringer, L and Leal Filho, W and Djalante, R and Pinho, PF and Liwenga, E (2021) Global vulnerability hotspots: differences and agreement between international indicator-based assessments. *Climatic Change: an interdisciplinary, international journal devoted to the description, causes and implications of climatic change*, 169 (1-2). ISSN 0165-0009

---

**Downloaded from:** <https://e-space.mmu.ac.uk/629339/>

**Version:** Published Version

**Publisher:** Springer (part of Springer Nature)

**DOI:** <https://doi.org/10.1007/s10584-021-03203-z>


**Usage rights:** Creative Commons: Attribution 4.0

Please cite the published version

<https://e-space.mmu.ac.uk>

---

# Global vulnerability hotspots: differences and agreement between international indicator-based assessments

Daniel Feldmeyer<sup>1</sup>  · Joern Birkmann<sup>1</sup> · Joanna M. McMillan<sup>1</sup> · Lindsay Stringer<sup>2</sup> · Walter Leal Filho<sup>3,4</sup> · Riyanti Djalante<sup>5</sup> · Patricia F. Pinho<sup>6</sup> · Emma Liwenga<sup>7</sup>

**Climatic Change volume 169, Article number: 12 (2021)**  
**<https://link.springer.com/article/10.1007/s10584-021-03203-z>**

## Abstract

Climate change impacts and their consequences are determined not only by the intensity and frequency of different climatic hazards but also by the vulnerability of the system, society or community exposed. While general agreement exists about the importance of assessing vulnerability to understand climate risks, there is still a tendency to neglect global and regional vulnerability patterns because they are hard to quantify, despite their value in informing adaptation, disaster risk and development policies. Several approaches to quantifying global vulnerability exist. These differ in terms of the indicators they use and how they classify countries or regions into vulnerability classes. The paper presents the structure of selected approaches and explores two indices in depth. The aim of this paper is to assess the level of agreement between selected international indicator-based

---

This article is part of a topical collection on Risk & Vulnerability to Extreme Events: Dynamics and Future Scenarios, edited by Joern Birkmann and Matthias Garschagen

\* Daniel Feldmeyer [daniel.feldmeyer@ireus.uni-stuttgart.de](mailto:daniel.feldmeyer@ireus.uni-stuttgart.de)

<sup>1</sup> Institute of Spatial and Regional Planning, University of Stuttgart, Pfaffenwaldring 7, 70569 Stuttgart, Germany

<sup>2</sup> Department of Environment and Geography, University of York, York, England

<sup>3</sup> Department of Natural Sciences, Manchester Metropolitan University, Oxford Road, Manchester M15 6BH, UK

<sup>4</sup> Hamburg University of Applied Sciences, Research and Transfer Centre “Sustainable Development and Climate Change Management”, Ulmenliet 20, D-21033, Hamburg, Germany

<sup>5</sup> ASEAN Organisation, Jakarta, Indonesia

<sup>6</sup> Institute for Advanced Studies (IEA), Sao Paulo, Brazil

<sup>7</sup> Institute of Resource Assessment (IRA) - University of Dar Es Salaam, Salaam, Tanzania

assessments of vulnerability, at the level of climate regions. Results suggest that the two major global vulnerability assessments analysed largely agree on the location of the most and least vulnerable regions when these assessments are aggregated to a regional scale using the IPCC's climate regions. The paper then discusses the robustness of the information derived and its usefulness for adaptation, disaster risk and development policies. Measuring progress towards reducing vulnerability to climate change and hazards is key for various agencies and actors in order to be able to develop informed policies and strategies for managing climate risks and to promote enabling conditions for achieving the SDGs and building resilience.

**Keywords** Vulnerability · Hotspots · Indicators · Climate change · Global mapping

## 1 Introduction

Since the IPCC Special Report SREX (IPCC 2012) and the Fifth Assessment Report (AR5) (IPCC 2014a) of the Intergovernmental Panel on Climate Change (IPCC), there have been increasing efforts to quantify climate risk at a global scale. Such assessments include examinations of human vulnerability to both climate change and natural hazards (INFORM 2019; ND-GAIN 2019; Feldmeyer et al. 2017). These global assessments all make an important contribution to quantifying human vulnerability and thus to understanding climate risk.

Climate risk is not just determined by the likelihood of climate-related hazards (e.g. extreme heat, flooding, drought) but also by where these occur and how vulnerable the exposed systems are to these hazards (Birkmann 2013; IPCC 2014b, p. 3, IPCC 2019, p. 88). Vulnerability is defined by the IPCC as “the propensity or predisposition to be adversely affected” (IPCC 2018a, p. 560). A system is vulnerable when it is both susceptible to being harmed by (or is sensitive to) a hazardous event and lacks the ability to cope and adapt to this event (IPCC 2018a, p. 560). Adaptive and coping capacity are two important components of vulnerability—adaptive capacity being “the ability of systems, *institutions*, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences” (IPCC 2018a, p. 542) and coping capacity being “the ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term” (IPCC 2018a, p. 546).

While vulnerability is accepted as an important factor in determining climate risk, its quantification is lagging behind that of global exposure to climate hazards, preventing an effective and targeted adaptation process to reduce risk. Recent research developments and new methods, such as the Shared Socio-Economic Pathways (SSPs) (O'Neill et al. 2017), have improved the consideration of societal development in climate adaptation research. These tools are important for informing adaptation policies. However, there is a need for them to better capture the multi-dimensional factors that shape human vulnerability—such as issues of poverty, human wellbeing, inequality, access to basic services, governance and safety nets for people at risk—in order to be able to address these issues more effectively. This information and analysis is missing at the transnational scale and needs consideration in order to capture all parts of the risk equation and effectively reduce negative consequences. Global vulnerability assessments have the potential to capture such factors and thus support better exploration of social scenarios and improve the SSPs. Existing global assessments of climate risk and vulnerability (INFORM 2019; Hallegatte et al. 2016; Birkmann and Welle 2016; Feldmeyer et al. 2017; Cardona and Carreño 2013; Birkmann et al. 2011) each use different

approaches anchored in different schools of thought. Global climate risk assessments that include measurement of vulnerability to climate change and natural hazards consider a variety of different factors that operationalize human vulnerability (INFORM 2019; Feldmeyer et al. 2017; Birkmann and Welle 2016; ND-GAIN 2019). Likewise, different global vulnerability assessments use different indicator sets to assess and evaluate levels of national vulnerability. Some global assessments encompass indicators that measure wealth and/or poverty, education and access to basic services; others capture in addition issues of governance (state fragility, corruption) and conflict. Despite the use of different indicators, these studies agree that vulnerability to climate change and natural hazards is multi-dimensional and requires the use of indicators that represent these diverse themes and dimensions.

Climate hazard information must be complemented with vulnerability information in order to provide a sound information base for decision-making. This has been underscored within IPCC reports since 2012 (IPCC 2012), including the last IPCC assessment report (IPCC 2014a) and the newer IPCC special report (SROCC / IPCC 2019), which have repeatedly highlighted the need to not only to focus on climate hazards but also to consider exposure and vulnerability (see the so called propeller figure, e.g. IPCC 2012). Newer IPCC Assessment Reports use geographical reference regions to analyse global climate change and related hazards (IPCC 2013). An urgent question is whether such regions—referred to as “climate regions”—intended for the analysis of physical phenomena of climate change can also be used to assess human vulnerability. If this is possible, it would provide a way to visualize human vulnerability issues in a way that is compatible with hazard data and disregards national boundaries.

Against this background, the paper addresses the following research questions:

- a) Can the results of quantitative vulnerability analyses be usefully aggregated from the national level up to the level of physical climate regions to complement climate hazard assessments?
- b) To what extent do these assessments agree on the classification of regions in terms of their level of vulnerability (i.e. low versus high vulnerability and variance)?
- c) What kind of spatial patterns emerge when assessing human vulnerability at the level of climate regions?

We answer these questions by comparing the approaches of two prominent global risk assessments: the INFORM Index (Marin-Ferrer et al. 2017) and the WorldRiskIndex (Birkmann et al. 2011; Birkmann and Welle 2016). We chose to compare these two indices in more detail because both indicator systems aim explicitly to capture human vulnerability, while other indices, such as the Global Climate Risk Index (Germanwatch 2019), primarily focus on past harm and losses rather than vulnerability to assess climate risks (e.g. Number of deaths, Sum of losses in US\$ in purchasing power parity). Furthermore, these two indices assess vulnerability more comprehensively with larger sets of indicators capturing context conditions as well as issues of access to resources, information and education, which are particularly relevant when aiming to reduce community and individual vulnerability. Additional justifications for focusing on these two indices are (a) their international orientation, (b) the fact that they are widely acknowledged as valid, (c) their inclusive nature, which take into account trends in both industrialized and developing nations, (d) the fact that they offer concrete support for adaptation efforts, and (e) based on reliable data sources, e.g. World Bank, Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO).

These two assessments (WorldRiskIndex and INFORM Index) were undertaken by different institutions and groups, and each contributes in different ways to a more comprehensive representation of human vulnerability compared with conventional economic risk assessments. In many senses these two approaches are similar in their understanding of vulnerability as conditions that make people more susceptible and likely to face adverse consequences in the context of climate change and extreme events independent of the hazard intensity or past fatalities and harm. Each of these global assessments also has their limitations. Indicator-based quantitative assessments of vulnerability can only capture specific characteristics and not all aspects that determine human vulnerability to climate change hazards. Furthermore, the use of mean values for factors such as poverty has been criticized (Pelling and Garschagen 2019). Nevertheless, the global vulnerability patterns uncovered by these assessments provide new insights into which regions should be prioritized for adaptation and vulnerability reduction, and indicate where issues of governance and state failure are major factors of concern.

In this paper, we analyse the 2019 results of the vulnerability components of the INFORM Index (INFORM 2019) and WorldRiskIndex (Feldmeyer et al. 2017). This detailed comparison of the INFORM and WorldRiskIndex is done by first aggregating the results of the two indices from country-level vulnerability rankings to regional rankings, adapting the climate regions used by climate modellers contributing to the IPCC Sixth Assessment Report (AR6) (IPCC 2020). Climate regions are spatial boundaries delineated for the purpose of better representing climatic data and model result a sub-continental scale. These regions are designed through the lens of physical climate science and disregard sovereign borders. This means they lack the socio-economic dimension at the same spatial scale which often leads to a hazard focused perspective and the negation of the socio-economic dimension at this scale. The IPCC also calls for more integrated perspectives linking climate hazard, exposure and vulnerability information in order to assess risk (IPCC 2014b). Therefore, it is important to examine the ability to aggregate socio-economic and demographic information for assessing vulnerability at the level of climate regions. Aggregation and comparison of the two global vulnerability assessments reveal that although there are differences in how the assessments rank the vulnerability of countries in certain regions, they do largely agree on the regions of high human vulnerability to climate change risks, despite their use of different indicators.

In this paper, we first describe the state of the art of global climate risk and vulnerability assessments. Thereafter, we compare two global assessments—namely the WorldRiskIndex and the INFORM Index. We then examine the results of the two indices at the level of climate regions in detail. Finally, we discuss the benefits and limitations of such assessments and our proposed methodology used to represent human vulnerability at the level of physical climate regions.

## 2 State of the art of risk and vulnerability assessment

### 2.1 Four global approaches

A variety of different assessment approaches exist, based on different schools of thought and therefore based on different indicators, each with a different focus, leading to different results (Birkmann et al. 2021a; Birkmann et al. 2021b; Garschagen 2021). To capture the variety in assessing risk and human vulnerability, the following section

provides an overview of key differences and similarities of four approaches, with global orientation, acknowledged as valid and including a link to adaptation.

The INFORM Index was developed by international experts of the EU's Joint Research Center. It uses a composite indicator system that identifies and ranks countries at risk to climate change and natural hazards, focusing on national capacities to respond to crises and vulnerability to disaster risk. INFORM aims to support a proactive crisis and disaster management by means of assessing key dimensions of risk: hazard, exposure, vulnerability and lack of coping capacity. The index is based on 54 core indicators, applied to at least the five previous years of data to assess the risk that specific hazards and crises pose to each country (Marin-Ferrer et al. 2017).

The WorldRiskIndex is a mathematical model and a visualization and communication tool that combines the physical and spatial exposure to natural hazards with societal vulnerability, presenting risk values and charts. The methodology was developed by Birkmann and Welle in close cooperation with colleagues from the United Nations University and practitioners of the Alliance Development Works (see Birkmann et al. 2011). The index is based on the analysis of 28 indicators, assessing global risk patterns of over 170 countries. The WorldRiskIndex encompasses human vulnerability as a core component, capturing it in terms of three components: susceptibility, coping capacities and adaptive capacities. The analysis of vulnerability identifies regions and countries that have severe difficulties in dealing with natural hazards and climate change and those countries that are in a better position to cope with and adapt to these impacts. The indicators measure both specific living conditions (for example, access to basic infrastructure and services) and coping capacities determined by larger framework conditions (such as the governance context, which influences people's ability to deal with extreme events directly or indirectly, such as insurance coverage or corruption) (Birkmann et al. 2011; Welle and Birkmann 2015; Birkmann and Welle 2016). Individual indicator values are transformed and aggregated and thereafter mapped within a Geographic Information System (GIS) to visualize the relative level of vulnerability of different regions and countries.

The Global Climate Risk Index is calculated annually and examines the extent to which countries and regions have been affected by the impacts of weather-related loss events (e.g. storms, floods, heat waves) considering data from the past decade (i.e. the 2019 report used data from 1998 to 2017). The Climate Risk Index aims to serve as a kind of information and warning system, showing existing vulnerability that may further increase in regions where extreme events will become more frequent or more severe due to climate change. The index especially focuses on the effects of past impacts of weather-related events on countries and regions. The Global Climate Risk Index 2019 shows that high-income countries experienced the impacts of climate change more strongly in this year than in previous decades. In this regard, the losses and damages considered within the index also hint towards the necessity to act both in developing and developed countries.

The Notre Dame Global Adaptation Index (ND-GAIN) has been published annually by the University of Notre Dame since 1998. This index ranks countries' vulnerability to climate change and readiness to adapt. The goal of the index is to inform decision-makers in the public and private sector to allow them to prioritize investments and increase resilience. Readiness is measured within social, economic and governance dimensions. The vulnerability matrix is organized into six life-supporting sectors (health, food,

ecosystems, habitat, water, infrastructure) and three dimensions (adaptive capacity, sensitivity and exposure).

## 2.2 Comparison of the assessment approaches

All four assessments described above have a resolution at the individual country scale. While each uses a different set of indicators, most contain parameters that cover aspects of economic poverty, inequality, access to basic infrastructure services (water, sanitation), life expectancy, adult literacy rate and the level of social protection (e.g. insurance). The assessments differ, for example, in terms of their consideration of aspects of governance, such as corruption and conflict, as well as in terms of their consideration of losses experienced in the past (see Feldmeyer et al. 2017).

The Global Climate Risk Index differs most significantly from the other three (Table 1), as it documents what happened in a specific period. It does not include a probabilistic analysis of frequencies and return periods of the events. ND-GAIN is also different from the other indices in that it defines exposure as a component of vulnerability. The WorldRiskIndex and INFORM have separate exposure and vulnerability components, with INFORM also having a component called “lack of coping capacity”.

In terms of the hazard and exposure components of risk, the four approaches include different aspects (Table 2). The WorldRiskIndex focuses on exposed population to natural hazards, namely, earthquakes, cyclones, floods, drought and sea level rise. INFORM considers exposure in a similar way, in that it considers people exposed to natural hazards but also considers human conflict. The Global Climate Risk Index specifically addresses hazards intensified by climate change and thus excludes earthquakes but includes temperature extremes and mass movements. ND-GAIN uses a significantly different approach in that it defines exposure as “the extent to which human society and its supporting sectors are stressed by the future changing climate conditions” (Chen et al. 2015, p. 3) and thus considers the effects of climatic change on a range of sectors using different exposure indicators for each sector—for example, for the water sector one exposure indicator is “projected change of annual groundwater recharge” (Chen et al. 2015, p. 16).

## 3 A comparison of the INFORM index and WorldRiskIndex

### 3.1 Comparison of the indicators used by each index

In this section we compare the indicators used by the WorldRiskIndex and INFORM Index to measure vulnerability and identify similarities and differences between the two indices. We selected these two indices to compare, of the four described above, because they most comprehensively and explicitly assess vulnerability. They also clearly differentiate exposure and vulnerability. The WorldRiskIndex considers vulnerability a function of susceptibility, lack of coping and lack of adaptation, while INFORM considers vulnerability as a function of socio-economic vulnerability and vulnerable groups and calculates lack of coping capacity separately (see Table 1).

A closer examination of these vulnerability components of the WorldRiskIndex and INFORM found that these have eight indicators in common (Table 3), namely,

**Table 1** Comparison of the main dimensions and framing of risk and vulnerability in the ND-GAIN, WorldRiskIndex and INFORM approach (ND-GAIN 2019; INFORM 2019; Germanwatch 2019; Birkmann and Welle 2016)

ND-GAIN	WorldRiskIndex				INFORM				Climate Index		
Vulnerability	Exposure	Vulnerability			Hazard and exposure	Vulnerability		Lack of Coping Capacity	Risk		
Exposure Sensitivity	Adaptive Capacity	Natural	Susceptibility	Coping Capacity	Adaptive Capacity	Natural	Human	Socio-Economic	Vulnerable Groups	Institutional Infrastructure	Climate hazards



**Table 2** Hazards considered by the ND-GAIN, WorldRiskIndex, INFORM and Global Climate Risk Index (ND-GAIN 2019; INFORM 2019; Germanwatch 2019; Birkmann and Welle 2016)

ND-GAIN	WorldRiskIndex	INFORM	Global Climate Risk Index
The extent to which the following sectors are stressed by the future changing climate conditions: <ul style="list-style-type: none"> <li>· Food</li> <li>· Water</li> <li>· Health</li> <li>· Ecosystem services</li> <li>· Human habitat</li> <li>· Infrastructure</li> <li>· Governance readiness</li> <li>· Social readiness</li> </ul>	The potential average annual number of individuals who are exposed to: <ul style="list-style-type: none"> <li>· Earthquake</li> <li>· Cyclones</li> <li>· Floods</li> <li>· Droughts</li> <li>· Sea level rise</li> </ul>	The expected number of people located within the hazard zone for each type of the following hazards: <i>Natural</i> <ul style="list-style-type: none"> <li>· Earthquake</li> <li>· Cyclones</li> <li>· Flood</li> <li>· Droughts</li> <li>· Tsunami</li> </ul> <i>Human</i> <ul style="list-style-type: none"> <li>· Projected conflict risk</li> <li>· Current conflict intensity</li> </ul>	Deaths and economic losses (absolute and proportional) due to the following hazards: <ul style="list-style-type: none"> <li>· Storm</li> <li>· Floods</li> <li>· Temperature extremes</li> <li>· Mass movements</li> </ul>

the Gini Coefficient, adult literacy rate, access to improved sanitation facilities, access to improved water source, physician density, health expenditure per capita, corruption perception index and prevalence of undernourishment. Moreover, two similar indicators are measured by different indicators: poverty and gender inequality. The WorldRiskIndex has 12 additional indicators with emphasis on the environment. INFORM has 21 additional indicators focusing more on connectivity and diseases.

### 3.2 Comparing vulnerability assessments at the level of climate regions: INFORM and WorldRiskIndex

#### 3.2.1 Methodology

In this section we aggregate the country-level vulnerability rankings of the WorldRiskIndex and INFORM Index to the level of climate region. We then average the two indices to deliver an average vulnerability ranking for each region, achieving an overall ranking of regions in terms of their relative vulnerability. Finally, we calculate the level of agreement between the two indices at this aggregated scale. These steps will be explained in more detail in the following paragraphs.

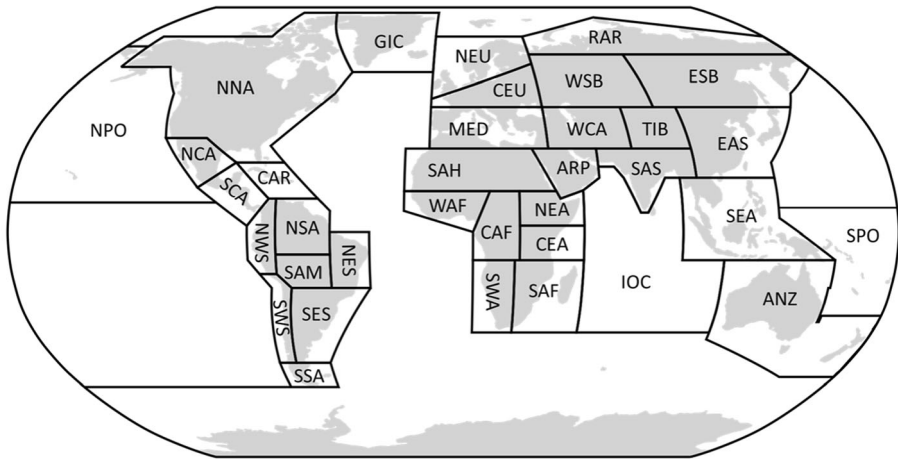
On a global scale, socio-economic statistics are accessible for individual countries. Climate impacts, in contrast, and cross borders are better approximated by climate regions. Climate regions are geographic areas defined for use in the context of the IPCC Assessment Reports for the purpose of assessing the climate projections produced by climate modellers. We use climate regions in order to better link vulnerability information with information on climate change and its impacts, adapting those used in the Sixth Assessment Report (AR6) for our own purposes of aggregating vulnerability rankings. Figure 1 displays the climate regions used for the analysis of socio-economic vulnerability. With the spatial join tool of ArcGIS 10.5.1 and the intersect option selected, countries were allocated to climate regions. Some changes had to be made to the climate regions

**Table 3** comparison of the indicators used to assess different dimensions of human or societal vulnerability of the INFORM and WorldRiskIndex (INFORM 2019; Birkmann and Welle 2016)

Common indicator categories assigned by authors	<b>INFORM</b> Indicators of Vulnerability & Lack of Coping Capacity	<b>WorldRiskIndex</b> Indicators of Vulnerability
Income equality	Gini Coefficient	Gini-Index
Poverty	Multidimensional Poverty Index	Extreme poverty (pop living on less than 1.25 USD)
Development	Human Development Index	Gross Domestic Product per capita
	Public Aid per capita	
	Net ODA Received (% of GNI)	
Gender equality	Gender Inequality Index	Gender parity in education
		Share of female representatives in the National Parliament
Corruption	Corruption perception Index	Corruption perception index
Governance	Government effectiveness	Failed State Index
Literacy	Adult literacy rate	Adult literacy rate
Education		Combined gross school enrolment
Health	Physicians density	Number of physicians per 10,000 pop
	Health expenditure per capita	Public health expenditure
		Private health expenditure
	Child Mortality	Life expectancy at birth
	Prevalence of HIV-AIDS above 15-years	Number of Hospital beds per 10,000 pop
	Tuberculosis prevalence	
	Malaria mortality rate	
Measles immunisation coverage		
Nourishment & Food Security	Prevalence undernourishment	Share of undernourished population
	Children underweight	
	Average dietary supply adequacy	
	Domestic Food Price Level Index	
	Domestic Food Price Volatility Index	
Sanitation	Access to improved sanitation facilities (% of pop with access)	Share of population without access to improved sanitation
Drinking water	Access to improved water source (% of pop with access)	Share of population without access to clean water
Disaster preparedness	Hyogo Framework for Action	Insurance
	Relative number of affected population by natural disasters in the last three years	
Environment		Protection of biodiversity and habitats
		Forest management
		Agricultural management
		Water resources
Infrastructure	Road density (km of road per 100 km <sup>2</sup> of land area)	
	Mobile cellular subscription (per 100 people)	
	Internet Users (per 100 people)	
	Access to electricity (% of population)	
Other vulnerable groups	Number of refugees, returned refugees, internally displaced persons (absolute and relative)	Dependency ration (proportion of under 15- and above 65-year olds in relation to working pop)

Same indicators
  Similar indicators
  Different indicators

because vulnerability rankings are based on socio-economic data, which is mostly collected at a country-level. This means that, for example, although North America contains



<b>ANZ</b> Australia/New Zealand	<b>NES</b> N.E. South America	<b>SEA</b> S.E. Asia
<b>ARP</b> Arabian Peninsula	<b>NEU</b> N. Europe	<b>SAF</b> S.E. Africa
<b>CAF</b> Central-Africa	<b>NNA</b> N. North America	<b>SES</b> S.E. South America
<b>CAR</b> Caribbean	<b>NCA</b> N. Central America	<b>SPO</b> S. Equatorial Pacific Ocean
<b>CEA</b> Central E. Africa	<b>NPO</b> N. Pacific Ocean	<b>SSA</b> S. South America
<b>CEU</b> Central Europe	<b>NSA</b> N. South America	<b>SWA</b> S.W. Africa
<b>EAS</b> E. Asia	<b>NWS</b> N.W. South America	<b>SWS</b> S.W. South America
<b>ESB</b> E. Siberia	<b>RAR</b> Russian Arctic	<b>TIB</b> Tibetan Plateau
<b>GIC</b> Greenland/Iceland	<b>SAH</b> Sahara	<b>WAF</b> W. Africa
<b>IOC</b> Indian Ocean	<b>SAM</b> South American Monsoon	<b>WCA</b> W. Central Asia
<b>MED</b> Mediterranean	<b>SAS</b> S. Asia	<b>WSB</b> W. Siberia/E. Europe
<b>NEA</b> N.E. Africa	<b>SCA</b> S. Central America	

Fig. 1 Adapted IPCC climate regions for the analysis of socio-economic vulnerability

several different climate regions, it only contains two countries, so we therefore had to combine the seven climate regions into one North American region. Similarly, for the Indian Ocean, New Zealand and Australia, East Europe and Western Siberia and South and Equatorial several smaller climate regions were merged to the higher order of climate regions. Arctic-Ocean, East-Antarctica, West-Antarctica and South-Ocean climate regions were not included.

The WorldRiskIndex calculates vulnerability as a composite index of the dimension susceptibility, lack of coping and lack of adaptation. INFORM calculates vulnerability as socio-economic vulnerability and vulnerable groups, and calculates lack of coping capacity separately (see Table 1). We first combine the vulnerability and lack of coping capacity indices of INFORM to make a composite vulnerability index that is comparable to the vulnerability component of the WorldRiskIndex. Subsequently, we calculate the mean vulnerability score for each climate region based on both indices. We then use these vulnerability scores to rank the climate regions (1 low to 35 high) for each index. We use this ranking method because one

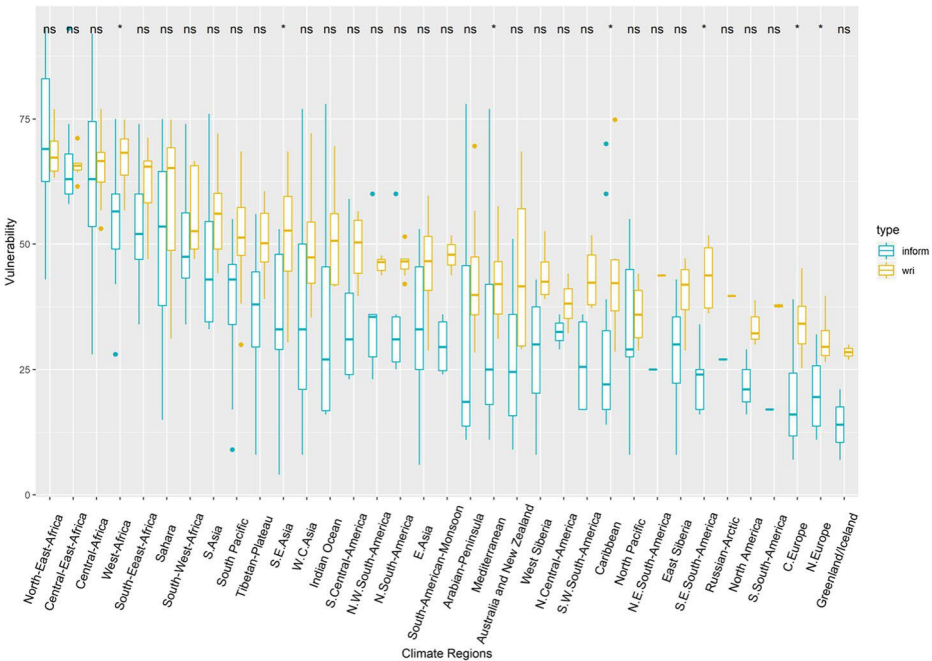
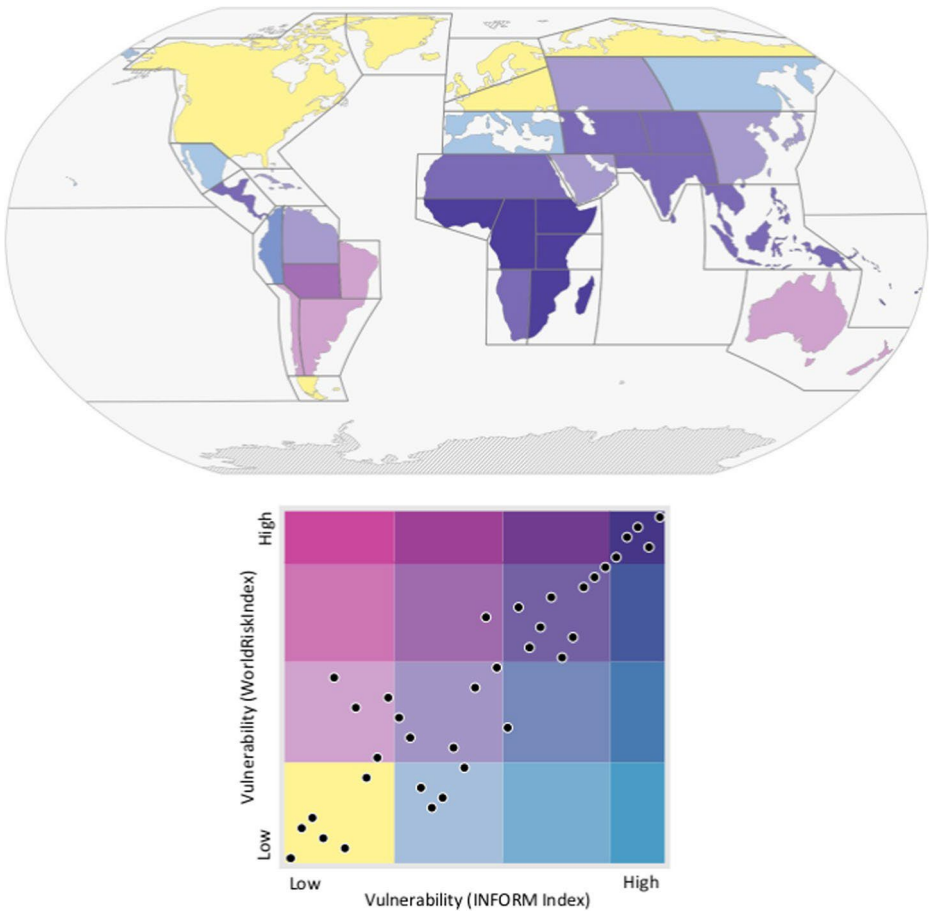


Fig. 2 Variance of vulnerability within climate regions (Box-plots: ns:  $p > 0.01$ ; \*:  $p < 0.01$ )

index (WorldRiskIndex, see Fig. 2) had in general higher vulnerability scores, but for the classification of countries or regions, the relative ranking is more important and what we aim to analyse.

We then compare the ranking of the climate regions according to vulnerability scores given by the WorldRiskIndex and the INFORM Index as follows (see Fig. 3). Firstly, we plot the 35 climate regions on a scatter plot according to how they were ranked according to their vulnerability—on the x-axis showing the rankings derived from the INFORM index and on the y-axis those from the WorldRiskIndex. We then classify the 35 climate regions into four classes (i.e. ranks 1–10, 11–20, 21–30, 31–35 to make 4 classes of vulnerability from lowest to highest). We then overlay these two classifications of the climate regions to create 16 classes using a cartography method described by Strode et al. (2019) called a “bivariate choropleth map”. Each of the 16 classes is assigned a colour, as shown behind the scatter plot, and each climate region is mapped according to the colour of the class in which they are ranked (Fig. 3). The darker more saturated colours show regions of higher vulnerability. This map and corresponding scatter plot diagram show the spatial pattern of vulnerability globally and also shows the agreement between the two indices on this pattern. This approach therefore includes the assessment of uncertainties in line with the IPCC AR5: “Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement” (Mastrandrea et al. 2010, p.2). We conduct the spatial analysis in ArcGIS 10.5.1, the data modelling with R in Rstudio.



**Fig. 3** Bivariate choropleth map and scatter plot diagram legend showing the agreement between two global vulnerability indices (WorldRiskIndex and INFORM Index) when ranking of climate regions according to their vulnerability. Darker colours show regions of higher vulnerability. The diagram legend shows how the 35 climate regions are ranked by each index. Source: Own map based on the rankings of the INFORM Index (INFORM 2019) and the WorldRiskIndex (Feldmeyer et al. 2017)

### 3.2.2 Results

**Aggregation of, and agreement between, vulnerability indices** Figure 2 shows the results of the aggregation of the country-level vulnerability scores of the INFORM and WorldRiskIndex to climate regions. The box plot shows the average vulnerability score for each climate region for each index, as well as the spread and variability of the country-level scores within each region. It can be seen that within each climate region there is often a large variance, especially in the larger climate regions. Overall, the WorldRiskIndex ranks regions to be more vulnerable than the INFORM Index does, with North-East Africa as the single exception. The test for statistical difference of the mean values (Wilcoxon test) with alpha 0.01, shows for 35 climate regions, there is no significant difference (ns), while statistically significant differences were revealed for seven regions (W. Africa, S.E. Asia, Mediterranean, Caribbean, S.E. South-America, Central Europe, North Europe) (see Fig.

2). Both assessments agree on the ranking of climate regions for most of the regions examined.

For example, there is high agreement on the three most vulnerable climate regions. In contrast, the mean values of two of the three lowest regions are significantly different between the WorldRiskIndex and INFORM. The disagreement for West-Africa is rooted in a very high lack of coping within the WorldRiskIndex, with 85 points, and a lower score for vulnerable groups in INFORM, with 42 points. For Central Europe the mean vulnerability of the WorldRiskIndex is 34 points, whereas in INFORM it is only 18 points. The interquartile range supports the aggregation on climate region scale, showing a clear trend and ranking of them. Moreover, in terms of vulnerability assessment, single outliers cannot counterbalance the overall regional trend. A single country that is much more vulnerable than the rest of the region might benefit and a single country much better is in danger of being affected negatively. Hence the regional classification gives important insights into the regional vulnerability level, despite single outliers.

Figure 3 shows that the two indices agree on the most and least vulnerable regions. While there is some disagreement, especially for regions in the middle of the rankings, there are no regions where the indices completely disagree (i.e. there are no cases in which one index ranks a region at the lowest end and the other at the highest end of the list of regions ranked by vulnerability). If the indices completely agreed on the order of regions from lowest to highest vulnerability, the dots of the scatter plot would be in a straight diagonal line from the bottom left to the top right corner of the graph—there is some deviation from this perfect agreement but there are no dots in the top left or bottom right corner of the scatter plot diagram, meaning there are no major disagreements.

The following paragraphs will take a closer look at some specific climate regions and how their ranking can be explained by the mean vulnerability scores of the two indices and their sub-components. The climate region Australia and New Zealand (ANZ) is judged to be more vulnerable than North America (Fig. 3) by both the WorldRiskIndex, which rates ANZ according to the mean vulnerability score 10 points more vulnerable than North America, and INFORM, which calculates ANZ to be 5 points more vulnerable than North America. ANZ is considered more vulnerable in every aspect of both the WorldRiskIndex (susceptibility, lack of coping, lack of adaptation) and INFORM (socio-economic vulnerability, vulnerable groups) indices. The most significant difference between the two regions is their susceptibility as rated by the WorldRiskIndex, which rates ANZ as 13 points more susceptible than North America. INFORM considers ANZ to be more socio-economically vulnerable but less vulnerable in regard to vulnerable groups. ANZ is also considered more vulnerable than South East South America (SES), although the WorldRiskIndex considers them to have the same level of vulnerability. In addition, the INFORM considers ANZ more vulnerable due to the indicators of vulnerable groups (16 points higher in ANZ than in SES).

Comparing South Central America (SCA) and the Sahara (SAH) climate regions, the latter is more vulnerable. INFORM rates SAH as 16 points more vulnerable than SCA, and the WorldRiskIndex rates it 11 points more vulnerable. The high rating in the case of INFORM is due to more people belonging to vulnerable groups (18 points higher in SAH than in SCA) and in the case of the WorldRiskIndex is due to a higher susceptibility rating (14 points higher in SAH than in SCA).

For most of the climate regions, the relative vulnerability rankings of each index did not differ by more than 3 ranks out of 20 and for no climate region was the difference between the indices more than 6 ranks. This suggests a high level of agreement between the vulnerability assessments of the INFORM Index and WorldRiskIndex.

**Global spatial patterns of vulnerability** High agreement was found for regions of very high vulnerability. In particular, West, East and Central Africa and South Asia and in part the Pacific Islands were determined to be highly vulnerable by both indices. Agreement between INFORM and the WorldRiskIndex exists despite the use of different indicators, leading us to conclude that there is high confidence as to the locations of major vulnerability hotspots on a global scale.

The two global assessments examined in detail used 56 indicators overall to assess different dimensions of vulnerability. There are several differences in the indicator sets used, especially in the measurement of environmental and governance factors. However, comparison of the two assessments reveal that there is high agreement regarding global hotspots of vulnerability (regions classified as highly vulnerable) at the level of climate regions. It was found that the impact of differences in the indicators used seems to be less significant for countries classified as highly vulnerable. The combined ranking thus shows high agreement on those regions ranked as highly vulnerable, while there is less agreement on those ranked as having medium or low vulnerability, for example, the climate regions Southeast South America (SES) and South American Monsoon (SAM). In this regard, the hotspots of vulnerability are robust considering that even differences in the sets of indicators do not change them significantly.

Various regions in Africa (e.g. particularly West-Africa, Central-Africa, North-East-Africa, South-East Africa and Sahara) followed by South Asia appear as climate regions highly vulnerable to climate change due to their socio-economic, demographic, environmental and governance conditions. For example, the proportion of people living with less than 1.9USD a day is 60 times higher in the climate region South-East-Africa compared with the climate region Central-Europe. Next to different levels of poverty, it is also inequality which is higher in most vulnerable regions. In South-East-Africa inequality measured with the Gini coefficient is 1.8 times higher than for Central-Europe. Poverty and inequality are acknowledged as factors that increase human vulnerability to climate change.

In addition, Southeast and Central Asia and the Pacific Island Regions are characterized by high levels of human vulnerability. Central America, parts of South America and East Asia follow as vulnerable regions thereafter, showing still a relatively high level of human vulnerability (see Fig. 3). In these regions, climate change adaptation and risk reduction require not only information about future climatic stressors but also strategies that address the deeper underlying issues that cause human vulnerability and that make people more susceptible to the actual and potential impacts of climate change (Thomas et al. 2018). In these regions, strategies for climate resilience and climate resilient development pathways must address development issues not only at the local or national scale but also particularly at the regional scale, in order to ensure that enabling framework conditions for climate change adaptation of communities are enhanced and strengthened.

In contrast to the regions mentioned above, the regions around the Mediterranean, Australia and New Zealand and Southern South America show a lower human vulnerability level. North and Central Europe and North America rank among those regions that show a low level of human vulnerability in comparison to other regions (see Fig. 3). The level of agreement in the classification of low and medium vulnerable regions, however, is lower compared with the ranking of climate regions in terms of high vulnerability.

### 3.2.3 Discussion

The comparative assessment of two global index systems for vulnerability points to various similar climate regions is classified as highly vulnerable, and therefore there is high agreement regarding global hotspots of human vulnerability. However, there is medium agreement in



terms of the ranking of climate regions into medium and low vulnerability levels. The analysis revealed that even if larger indicator systems use in part different indicators for assessing human vulnerability, certain regions appear to be consistently ranked as most vulnerable. Therefore, there appear to be structural differences between the climate regions. Consequently, regions with a high level of vulnerability have a strong predisposition to be negatively affected by climate change due to a variety of context conditions that make them more susceptible to the impact and adverse consequences of sudden-onset and slow-onset climate hazards. Furthermore, communities in these regions face the challenge that national institutions and capacities are severely constrained to support risk reduction and adaptation, such as in Sub-Saharan Africa. Various regions classified as highly vulnerable also face governance challenges and problems in terms of chronic poverty.

The identification of spatial hotspots of human vulnerability at the global level is an important prerequisite for the formulation and development of preventive adaptation and risk reduction measures at regional level. In this regard, the two indicator-systems examined in detail fulfil their function to serve as a communication and visualization tool and inform policies or drive behavioural changes (e.g. Becker et al. 2017 ; Feldmeyer et al. 2021). The global hotspots identified are a first layer of information that show where, independent of a specific hazard, attention and action are needed to improve enabling conditions for adaptation.

The relative assessment of human vulnerability, however, also has some limitations. For example, countries in Latin America are also vulnerable to climate change; however, they often appear to be have a medium level of vulnerability but do not appear to be hotspots in the global analysis, since various climate regions in Africa and also South Asia are more constrained and characterized by higher levels of human vulnerability. Consequently, the global maps presented show and define human vulnerability in relative terms—highly vulnerable regions are more vulnerable compared with other regions at the global scale. This information is primarily useful for a first global screening, while more detailed information and assessments are needed if specific countries or sectors are going to be addressed. Within large countries and large climate regions, specific pockets of highly vulnerable areas are barely visible. This is because many indicators focus on averages or distributional patterns at the national scale (e.g. GINI index). For example, the newest report on extreme poverty and inequality in the USA and the UK (Alston 2018) shows that extreme poverty is increasing in some high-income countries despite a relatively low average poverty level at the national scale. However, the context in which these groups might experience climate-related hazards is different from that of highly vulnerable climate regions, such as those in Africa, which are characterized by overall high levels of poverty, limited access to functioning infrastructure and governance challenges. In addition, the vulnerability information might need to be complemented with information about present and future exposure patterns to climatic hazards, such as sea-level rise, flooding or droughts. In this context, also the medium vulnerability of some Pacific Islands is problematic, since it is likely that with severe increases in exposure, the overall risk will also increase.

This paper finds that there is lower agreement between the global vulnerability assessments examined in terms of regions classified as having medium vulnerability. For these regions, the indicators that are different between the two assessments seem to be playing a stronger role. For example, the WorldRiskIndex considers environmental aspects, while the INFORM Index considers more specific infrastructure indicators and issues of displacement. These differences might be less relevant in countries and regions classified as highly vulnerable, since in these regions, various indicators point towards significant challenges and contextual deficits that



make societies more susceptible to the impact of climate change. The cumulative effect of multiple challenges dominates the results for highly vulnerable region. Regarding the spatial pattern of human vulnerability, specific indicators are less influential. Overall clear differences between the climate regions emerge. This provides important contextual understanding of vulnerability for climate change adaptation at the level of physically defined climate regions. These indicators and assessments show structural development challenges that increase human vulnerability to climate change and simultaneously also constrain adaptation options independent of the specific hazards. These challenges are not equally distributed between climate regions; rather the assessment clearly reveals regional, spatial patterns that require spatially specific adaptation policies.

The paper also shows that the ranking of regions differs between the WorldRiskIndex and the INFORM Index and the variance of country values can be significant within regions. However, we demonstrated that the variance and disagreement between the assessments is overall lower in climate regions with particularly high or low vulnerability rankings. The study by Hagenlocher and Garschagen (2018) comparing five disaster risk indices, including WorldRiskIndex and INFORM, at the country level, concludes that for disaster risk, there is high agreement on low-risk and high-risk countries. In addition, Garschagen et al. (2021) conclude that spatial hotspots for socio-economic vulnerability at national scale are more robust and contain a higher agreement between the indicator systems examined than for exposure.

Overall, each of the global assessments underscore that climatic hazards of the same magnitude, intensity and frequency would cause significantly more harm, damage and suffering within regions classified as highly vulnerable (INFORM 2019, WorldRiskIndex 2019, Germanwatch 2019, Feldmeyer et al. 2017, Hallegatte et al., 2017). While it is crucial to reduce the exposure of people and assets to climatic hazards and to mitigate global warming, our results underscore that it is also essential to address challenges linked to high levels of inequality and poverty and a lack of access to safety nets for most inhabitants in these regions, if climate risks are to be reduced. This need emerges from the assessment of the overall vulnerability of climate regions and specific indicators, as shown above for poverty and the Gini-coefficient. That means risk reduction and adaptation have to address, next to climate hazards, also deeper structural development challenges, captured within the indicator system by, for example, income equality, poverty, literacy, corruption, health, nourishment and food security (Table 3). These findings are confirmed by studies that examine past impacts of climate-related hazards and disasters within different world regions (Formetta and Feyen 2019). However, even moderate changes in the global mean temperature—as identified in the recent IPCC 1.5 report (IPCC 2018b) and the newer published peer-reviewed literature (see Hoegh-Guldberg et al. 2019)—are likely to result in substantial increases in risk due to irreversible environmental degradation combined with high levels of vulnerability for regions such as West Africa and the Sahel or the Pacific.

## 4 Conclusion

This paper contributes to the literature by showing how international indicator-based assessments of vulnerability are comparable and to what extent different assessments point towards the same or towards different geographic areas in terms of high, medium and low vulnerability. Our analysis reveals that vulnerability can also be visualized at the level of physical climate regions

used by the IPCC and thereby can complement hazard information at this scale. Moreover, the comparison of two comprehensive vulnerability index systems (INFORM and WorldRiskIndex) showed that there is high agreement on most vulnerable and least vulnerable regions, even if different indicators are used. Thus, the two comprehensive global approaches for assessing human vulnerability come to the same conclusion in terms of regional hotspots of human vulnerability. The findings of the paper and the aggregated results of vulnerability at climate region scale contribute to a more comprehensive information base for adaptation and risk reduction. Various approaches within the international discourse, for example, the Reasons of Concern of past IPCC reports (IPCC 2007, 2012, 2014a) and also the discussion of Shared-Socio-Economic Pathways often avoid being spatially specific. While this approach is strategically useful for the communication of results to heads of state, a systematic and informed enhancement of climate risk management and climate resilient development requires also information on where regional or spatial priorities should be. In this regard, the paper shows not only climate regions that should be targeted as a priority but also reveals spatial patterns of human vulnerability that span over different climate regions. That means, independent of a specific climate hazard, international and transnational adaptation approaches are needed that can build capacities at the local, national and regional levels to enhance adaptation and risk reduction. While different approaches exist to measure vulnerability at the global scale, two very comprehensive approaches differ in terms of single-country values or specific indicators, but their relative ranking of vulnerability higher or lower compared with another country or region points in the same direction. Consequently, our paper provides evidence about the fact that high agreement and robustness exist in terms of the spatial patterns of high and low vulnerability at the level of climate regions. These global patterns can inform future adaptation and risk reduction policies in the sense that they indicate the importance of the coordination of such policies beyond national borders, particularly in climate regions classified as most vulnerable. These regions need a climate resilient development approach that addresses the broader development deficits.

Finally, the analysis also reveals limitations of the global assessments. The ranking of each region is influenced by a variety of factors and indicators. Consequently, the ranking of a region alone does not explain the specific development challenges and vulnerability profiles of the countries within it. Nevertheless, the global assessment does show that some global hotspots of human vulnerability have a spatial concentration, for example, in central and Sub-Saharan Africa. Our results underscore the necessity for stronger international cooperation and indicate that some of the structural vulnerabilities might require significant changes also in how we approach adaptation to climate change, shifting the focus from specific climate hazards towards the consideration of drivers of human vulnerability within these regions. This is an important message to agencies dealing with adaptation to climate change, human development programs and disaster risk reduction, since efforts to coordinate approaches to these issues are needed in regions where the lack of community resilience and the individual vulnerability of people is closely interwoven with structural vulnerability at the national and, importantly, the regional scale. Particularly in countries with persistent levels of poverty and severe governance challenges, international assistance and regional cooperation will be needed in order to provide conditions that enable different institutions and social groups to build resilience.

## ANNEXE I – CLIMATE REGIONS

**Table 4** Climate regions of the sixth assessment report and their adaptation for the present study

Region	Code	Aggregated
Greenland/Iceland	GIC	
N.E.Canada	NEC	North America
C.North-America	CNA	
E.North-America	ENA	
N.W.North-America	NWN	
W.North-America	WNA	
N.Central-America	NCA	
S.Central-America	SCA	
Caribbean	CAR	
N.W.South-America	NWS	
South-American-Monsoon	SAM	
S.South-America	SSA	
S.W.South-America	SWS	
S.E.South-America	SES	
N.South-America	NSA	
N.E.South-America	NES	
N.Europe	NEU	
C.Europe	CEU	
Mediterranean	MED	
West-Africa	WAF	
Sahara	SAH	
North-East-Africa	NEAF	
Central-East-Africa	CEAF	
South-West-Africa	SWAF	
South-Eeast-Africa	SEAF	
Central-Africa	CAF	
Russian-Arctic	RAR	
Russian-Far-East	RFE	
E.Siberia	ESB	East Europe West Siberia
E.Europe	EEU	
W.Siberia	WSB	
W.C.Asia	WCA	
Tibetan-Plateau	TIB	
E.Asia	EAS	
Arabian-Peninsula	ARP	
S.Asia	SAS	
S.E.Asia	SEA	
N.Australia	NAU	Australia/New Zealand
C.Australia	CAU	
S.Australia	SAU	
New-Zealand	NZ	
E.Antarctica	EAN	Not included
W.Antarctica	WAN	Not included
Arctic-Ocean	ARO	Not included
S.Pacific-Ocean	SPO	South Equatorial Pacific
Equatorial.Pacific-Ocean	SPO	
N.Pacific-Ocean	NPO	
S.Atlantic-Ocean	SAO	
Equatorial.Atlantic-Ocean	EAO	
N.Atlantic-Ocean	NAO	

Table 4 (continued)

Region	Code	Aggregated
Equatorial.Indic-Ocean	EIO	Indian Ocean
S.Indic-Ocean	SIO	
Arabian-Sea	ARS	
Bengal-Gulf	BOB	
South-Ocean	SOO	Not included

## ANNEXE II – INFORM AND WRI VULNERABILITY

Climate Regions	World Risk Index				INFORM Risk Index		
	Vulnerability				Vulnerability		
	Vulnerability	Susceptibility	Lack of Coping	Lack of Adaptation	Vulnerability	Socioeconomic	Vulnerable groups
Arabian-Peninsula	44,1	19,8	69,1	43,4	31,7	27,0	34,8
Australia and New Zealand	44,2	29,2	62,6	41,0	27,3	25,0	29,3
C.Europe	34,2	17,2	52,5	32,9	18,7	11,5	24,4
Caribbean	43,3	25,2	64,3	40,5	28,8	30,0	26,0
Central-Africa	64,3	49,2	86,8	56,9	62,7	61,2	63,8
Central-East-Africa	65,2	58,1	84,2	53,4	66,7	68,0	64,2
E.Asia	46,2	26,8	68,3	43,4	33,5	32,7	33,5
East Siberia	40,5	24,3	58,1	39,2	27,8	25,5	29,3
Greenland/Iceland	28,3	14,8	43,5	26,6	14,0	4,5	22,5
Indian Ocean	51,8	30,0	74,8	50,5	35,5	36,5	34,0
Mediterranean	42,1	20,7	65,6	40,0	32,8	25,1	38,3
N.Central-America	38,0	20,0	60,4	33,8	32,5	21,0	42,0
N.E.South-America	43,9	24,5	67,8	39,5	25,0	32,0	17,0
N.Europe	30,6	16,8	45,4	29,7	20,1	7,5	30,2
N.South-America	46,4	25,7	72,8	40,7	34,3	33,4	33,0
N.W.South-America	46,1	26,6	72,3	39,6	35,8	32,3	37,8
North-East-Africa	67,5	53,5	87,5	61,5	71,5	69,7	72,3
North America	33,5	16,5	49,9	34,2	22,0	12,7	29,0
North Pacific	36,1	19,7	54,5	34,3	33,9	33,6	32,1
Russian-Arctic	39,6	21,4	59,0	38,5	27,0	20,0	33,0
S.Asia	55,9	33,8	81,0	53,0	46,3	42,8	48,4
S.Central-America	49,2	29,5	74,4	43,8	35,1	38,3	31,3
S.E.Asia	52,1	31,9	76,2	48,1	35,0	36,4	32,7
S.E.South-America	44,7	27,0	67,2	40,0	23,2	31,6	13,2
S.South-America	38,0	20,8	58,7	34,6	17,0	21,5	12,5
S.W.South-America	44,2	27,3	67,7	37,7	26,0	31,5	19,8
Sahara	60,3	43,6	80,9	56,5	50,9	51,2	49,2
South-American-Monsoon	49,1	30,4	75,0	41,9	29,8	38,0	19,8
South-East-Africa	61,8	52,6	79,9	52,8	53,2	59,2	45,7
South-West-Africa	55,8	45,1	74,8	47,5	50,7	53,0	47,5
South Pacific	51,0	32,5	73,9	46,5	38,7	48,3	25,7
Tibetan-Plateau	51,8	31,9	74,5	49,1	35,8	37,6	33,5
W.C.Asia	49,5	26,8	74,4	47,3	37,6	32,0	41,2
West-Africa	66,4	51,9	85,1	62,1	54,2	63,3	42,3
West Siberia	44,6	24,7	65,9	43,3	28,0	25,3	29,2

Funding Open Access funding enabled and organized by Projekt DEAL.

## Declarations

**Conflict of interest** The authors have no conflicts of interest to declare that are relevant to the content of this article.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Alston, P. (2018): 1Statement on visit to the United Kingdom, by Professor Philip Alston, United Nations special rapporteur on extreme poverty and human rights. London. Available online at [https://www.ohchr.org/documents/issues/poverty/eom\\_gb\\_16nov2018.pdf](https://www.ohchr.org/documents/issues/poverty/eom_gb_16nov2018.pdf), checked on 3/11/2020
- Birkmann J (ed) (2013) Measuring vulnerability to natural hazards. Towards disaster resilient societies. UNU [United Nations University], 2nd edn. United Nations University Press, Tokyo
- Birkmann J, Feldmeyer D, McMillan JM, Solecki W, Totin E, Roberts DC, Trisos C, Jamshed A, Boyd E, Wrathall D (2021a) Regional clusters of vulnerability show the need for transboundary cooperation. *Environ Res Lett*, in press. <https://doi.org/10.1088/1748-9326/ac1f43>
- Birkmann J, Jamshed J, McMillan JM, Feldmeyer D, Totin E, Solecki W, Ibrahim ZZ, Roberts D, Bezner Kerr R, Poertner H-O, Pellling M, Djalante R, Garschagen M, Leal Filho W, Guha-Sapir D, Alegria A (2021b) Understanding human vulnerability to climate change: a global perspective on index validation for adaptation planning. *Sci Total Environ*, in press 150065. <https://doi.org/10.1016/j.scitotenv.2021.150065>
- Birkmann J, Welle T (2016) The WorldRiskIndex 2016: reveals the necessity for regional cooperation in vulnerability reduction. In *Journal Of Extreme Events* 03(02):1650005. <https://doi.org/10.1142/S2345737616500056>
- Birkmann, J.; Welle, T.; Krause, D.; Wolfertz, J.; Suarez, D. C. (2011): World Risk Index: Concepts and Results. In Alliance Development Works (Ed.): World Risk Report 2011. Governance and civil society. Berlin, pp 13–42
- Cardona O, Carreño M (2013) System of indicators of disaster risk and risk management for the Americas: recent updating and application of the IDB-IDEA approach. In: Birkmann J (ed) Measuring vulnerability to natural hazards. Towards disaster resilient societies, 2nd edn. United Nations University press, Tokyo, pp 251–276
- Chen, C.; Noble, I.; Hellmann, J.; Coffee, J.; Murillo, M.; Chawla, N. (2015): University of Notre Dame Global Adaptation Index. Country index technical report. University of Notre Dame. Available online at [https://gain.nd.edu/assets/254377/nd\\_gain\\_technical\\_document\\_2015.pdf](https://gain.nd.edu/assets/254377/nd_gain_technical_document_2015.pdf), checked on 3/11/2020
- Eckstein, D.; Hutflits, M.; Wings, M. (2019): GLOBAL CLIMATE RISK INDEX 2019. Who suffers Most from extreme weather events? Weather-related loss events in 2017 and 1998 to 2017. Germanwatch e.V. Bonn. Available online at [https://germanwatch.org/sites/germanwatch.org/files/Global%20Climate%20Risk%20Index%202019\\_2.pdf](https://germanwatch.org/sites/germanwatch.org/files/Global%20Climate%20Risk%20Index%202019_2.pdf), checked on 3/11/2020
- Feldmeyer D, Birkmann J, Welle T (2017) Development of human vulnerability 2012–2017. In *journal of extreme events* 04(04):1850005. <https://doi.org/10.1142/S2345737618500057>
- Feldmeyer, D., Nowak, W., Jamshed, A., Birkmann, J. (2021): An empirically developed vulnerability and resilience index based on damage data and OpenStreetMap. In *Science of Total environment* 774. DOI: <https://doi.org/10.1016/j.scitotenv.2021.145734>
- Formetta G, Feyen L (2019) Empirical evidence of declining global vulnerability to climate-related hazards. In *Global Environmental Change : Human and Policy Dimensions* 57:101920. <https://doi.org/10.1016/j.gloenvcha.2019.05.004>
- Garschagen M, Doshi D, Reith J, Hagenlocher M (2021) Comparing global climate and disaster risk indices – how consistent and robust are their results? *Clim Chang* in press
- Germanwatch (2019): GLOBAL CLIMATE RISK INDEX 2019. Who Suffers Most From Extreme Weather Events? Weather-related Loss Events in 2017 and 1998 to 2017. Germanwatch e.V. Bonn. Available online at [https://germanwatch.org/sites/germanwatch.org/files/Global%20Climate%20Risk%20Index%202019\\_2.pdf](https://germanwatch.org/sites/germanwatch.org/files/Global%20Climate%20Risk%20Index%202019_2.pdf), checked on 3/11/2020
- Hagenlocher, M.; Garschagen, M. (2018): Comparing global risk indices – how valid and consistent are their results? The American Association of Geographers' annual meeting, New Orleans, April 10–14, 2018

- Hallegatte, S.; Bangalore, M.; Vogt-Schilb, A. (2016): Socioeconomic resilience: multi-Hazard estimates in 117 countries: the World Bank
- Hoegh-Guldberg O, Northrop E, Lubchenco J (2019) The ocean is key to achieving climate and societal goals. In *science* (New York, N.Y.) 365(6460):1372–1374. <https://doi.org/10.1126/science.aaz4390>
- INFORM (2019): INFORM REPORT 2019. Shared evidence for managing crises and disasters. Available online at [https://drmkc.jrc.ec.europa.eu/inform-index/Portals/0/InfoRM/2019/Inform%202019%20WEB%20spreads%20\(3\).pdf?ver=2019-02-07-113610-123](https://drmkc.jrc.ec.europa.eu/inform-index/Portals/0/InfoRM/2019/Inform%202019%20WEB%20spreads%20(3).pdf?ver=2019-02-07-113610-123), checked on 3/11/2020
- IPCC (2007): Climate change 2007 synthesis report. With assistance of Core writing team, Pachauri, R.K and Reisinger, a.(eds. Available online at [https://www.ipcc.ch/site/assets/uploads/2018/02/ar4\\_syr\\_full\\_report.pdf](https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf), checked on 3/11/2020
- IPCC (2012): Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change. With assistance of 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. Cambridge, UK, and New York, NY, USA: Cambridge University press
- IPCC (2013): Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Cambridge University press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
- IPCC (2014a): Climate change 2014 synthesis report. With assistance of Core writing team, Pachauri, R.K and L.a. Meyer (eds. Available online at [https://www.ipcc.ch/site/assets/uploads/2018/02/SYR\\_AR5\\_FINAL\\_full.pdf](https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf), checked on 3/11/2020
- IPCC (2014b): Summary for policymakers. In IPCC (Ed.): Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. With assistance of Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press
- IPCC (2018a): Annex 1: Glossary. With assistance of Mathews J.B.R. In IPCC (Ed.): Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. With assistance of Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)
- IPCC (Ed.) (2018b): Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. With assistance of Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.). Available online at [https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15\\_Full\\_Report\\_High\\_Res.pdf](https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf), checked on 3/11/2020
- IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press
- IPCC (2020): The climate change ATLAS: datasets, code and virtual workspace. With assistance of Maialen Iturbide, Jose M. Gutierrez, Joaquin Bedia, Ezequiel Cimadevilla Alvarez, Rodrigo Manzanos, David Huard, Özge. Available online at <https://github.com/IPCC-WGI/Atlas>, updated on 2/28/2020, checked on 3/12/2020
- Kreft, S.; Eckstein, D.; Melchior, I. (2017): GLOBAL CLIMATE RISK INDEX 2017. Who suffers Most from extreme weather events? Weather-related loss events in 2015 and 1996 to 2015. Germanwatch e.V. Bonn. Available online at [https://germanwatch.org/sites/germanwatch.org/files/Global%20Climate%20Risk%20Index%202019\\_2.pdf](https://germanwatch.org/sites/germanwatch.org/files/Global%20Climate%20Risk%20Index%202019_2.pdf), checked on 3/11/2020
- Marin-Ferrer, M.; Vernaccini, L.; Poljansek, K. (2017): INFORM index for risk management. Concept and methodology version 2017. Publications Office of the European Union. Luxembourg. Available online at <https://drmkc.jrc.ec.europa.eu/inform-index/Portals/0/InfoRM/2017/INFORM%20Concept%20and%20Methodology%20Version%202017%20Pdf%20FINAL.pdf?ver=2017-07-11-104935-783>, checked on 3/11/2020
- ND-GAIN (2019): ND-GAIN Country Index. Available online at <https://gain.nd.edu/our-work/country-index/>, checked on 3/11/2020

- O'Neill B, Kriegler E, Ebi K, Kemp-Benedict E, Riahi K, Rothman DES et al (2017) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. In *Global Environmental Change* 42:169–180. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>
- Pelling M, Garschagen M (2019) Put equity first in climate adaptation. *Nature* 569(7756):327–329. <https://doi.org/10.1038/d41586-019-01497-9>
- Strode G, Morgan JD, Thornton B, Mesev V, Rau E, Shortes S, Johnson N (2019) Operationalizing Trumbo's principles of bivariate choropleth map design. *Cartographic Perspectives* 94:5–24
- Welle T, Birkmann J (2015) The world risk index – an approach to assess risk and vulnerability on a global scale. In *Journal of Extreme Events* 02(01):1550003. <https://doi.org/10.1142/S2345737615500037>