



A REGION AT RISK

THE HUMAN DIMENSIONS OF CLIMATE CHANGE IN ASIA AND THE PACIFIC

A REGION AT RISK

THE HUMAN DIMENSIONS OF CLIMATE CHANGE IN ASIA AND THE PACIFIC



Creative Commons Attribution 3.0 IGO license (CC BY 3.0 IGO)

© 2017 Asian Development Bank
6 ADB Avenue, Mandaluyong City, 1550 Metro Manila, Philippines
Tel +63 2 632 4444; Fax +63 2 636 2444
www.adb.org

Some rights reserved. Published in 2017.

ISBN 978-92-9257-851-0 (Print), 978-92-9257-852-7 (e-ISBN)
Publication Stock No. TCS178839-2
DOI:<http://dx.doi.org/10.22617/TCS178839-2>

The views expressed in this publication are those of the authors and do not necessarily reflect the views and policies of the Asian Development Bank (ADB) or its Board of Governors or the governments they represent.

ADB does not guarantee the accuracy of the data included in this publication and accepts no responsibility for any consequence of their use. The mention of specific companies or products of manufacturers does not imply that they are endorsed or recommended by ADB in preference to others of a similar nature that are not mentioned.

By making any designation of or reference to a particular territory or geographic area, or by using the term “country” in this document, ADB does not intend to make any judgments as to the legal or other status of any territory or area.

This work is available under the Creative Commons Attribution 3.0 IGO license (CC BY 3.0 IGO)
<https://creativecommons.org/licenses/by/3.0/igo/>. By using the content of this publication, you agree to be bound by the terms of this license. For attribution, translations, adaptations, and permissions, please read the provisions and terms of use at <https://www.adb.org/terms-use#openaccess>

This CC license does not apply to non-ADB copyright materials in this publication. If the material is attributed to another source, please contact the copyright owner or publisher of that source for permission to reproduce it. ADB cannot be held liable for any claims that arise as a result of your use of the material.

Please contact pubsmarketing@adb.org if you have questions or comments with respect to content, or if you wish to obtain copyright permission for your intended use that does not fall within these terms, or for permission to use the ADB logo.

Notes:

In this publication, “\$” refers to US dollars.

Corrigenda to ADB publications may be found at <http://www.adb.org/publications/corrigenda>

Figures, tables, and boxes without explicit sources are those of the authors.

ADB recognizes “China” as the People’s Republic of China, “Vietnam” as Viet Nam, and “Korea” as the Republic of Korea.

All photos are from ADB.



CONTENTS

FOREWORD	iv
ACKNOWLEDGMENTS	vi
TABLES, FIGURES, AND BOXES	vii
ABBREVIATIONS	ix
EXECUTIVE SUMMARY	x
INTRODUCTION	1
Part 1 ASIA AND THE PACIFIC AT A GLANCE	7
1.1 Asia and the Pacific: Its Geography	9
1.2 Asia and the Pacific: Its People	10
1.3 Asia and the Pacific: Its Economy	12
References—Introduction and Part 1	14
Part 2 CLIMATE CHANGE IN ASIA AND THE PACIFIC: OBSERVATIONS AND PROJECTIONS	17
2.1 Changes in Temperatures and Heat Extremes	19
2.2 Changes in Precipitation and Heavy Rainfall Events	24
2.3 Sea-Level Rise	27
2.4 Tropical Cyclones	33
2.5 Changes in Hydrology	38
2.6 Flooding Risks in Asian River Basins	42
References—Part 2	46
Part 3 CLIMATE CHANGE IMPACTS ON HUMAN SYSTEMS IN ASIA AND THE PACIFIC	53
3.1 Climate Change: Agriculture and Marine Ecosystems	55
3.2 Climate Change and Human Health	62
3.3 Climate Change and Urban Areas	69
3.4 Climate Change and Security	74
3.5 Climate Change and Migration	81
3.6 Climate Change and Trade Networks	95
References—Part 3	100
CONCLUSION	113

FOREWORD

The historic Paris Agreement of 2015 has acknowledged that the global climate crisis is arguably the greatest challenge human civilization faces in the 21st century. In this context, the role of the Asia and Pacific region is characterized by a double dichotomy that entails simultaneously high risks and significant opportunities. Proper analysis guided by adequate information can result in investment and policy choices that will continue to promote sustainable economic development and eradicate poverty in the region.

The first dichotomy relates to the region accounting for an increasing overall share of global emissions of greenhouse gases (GHGs) harming not only the world but the region itself. At the same time however, countries of the region have the unprecedented opportunity to break the GHG-intensive development path by rapidly modifying the historical model of industrial development. The rapidly decreasing costs of wind and solar power generation clearly indicates that consumption and production of the future could be driven by renewable energy sources, though the when and where of this great transition remain uncertain.

The second dichotomy pertains to the already observed and anticipated future impacts of anthropogenic global warming. On the one hand, the rapid economic and human development of the region renders societies less vulnerable to the familiar vagaries of the environment—such as heat waves, heavy precipitation or tropical cyclones. In particular, the shift away from agriculture as the core sector guaranteeing livelihoods and the associated economic diversification of the countries of the region help to increase resilience to weather extremes such as those experienced historically. Simultaneously however, the same developments have opened up new avenues of exposure and vulnerability. Coastal populations and assets are highly at risk from projected rises in sea level and the intensification of extreme weather events. Urbanized populations are exposed to heat stress hazards. National and increasingly integrated regional economic systems are vulnerable to disruptions in supply chain networks. Populations are migrating away from areas where climate change impacts represent an increasing threat.

These rapidly emerging new climate vulnerabilities in the Asia and Pacific region need to be addressed with a portfolio of strategies involving capacity building, preparedness programs, urban and rural planning, national and social security schemes, proactive migration and numerous others. Crucial preconditions for success are whole-systems and long-term thinking and planning, based on the best available data, analysis, and modeling.

This report aims to inform developing member countries of the most recent regional climate change projections and to assess the consequences of these changes for human systems. It also highlights gaps in the existing knowledge pertaining to the impacts of climate change, and identifies avenues where research continues to be needed. The information and insights presented in this report will contribute to scaling up the efforts of the Asian Development Bank (ADB) in building climate resilience in its developing member countries in the years and decades to come.

This report is the outcome of a collaboration of ADB with the Potsdam Institute for Climate Impact Research (PIK).

PIK was founded in 1992. With its team of researchers in the fields of natural and social sciences, PIK generates fundamental knowledge for sustainable development primarily through data analysis and computer simulations of the dynamic processes in the earth system, and through the study of social dynamics. PIK plays an active role in the international research community such as in the Intergovernmental Panel on Climate Change, and has initiated the Nobel Laureate Symposium on questions of global sustainability.

Since the early 1990s, ADB has provided support and assistance to countries of the region in coping with the adverse impacts of climate change. The nature and extent of this support and assistance have considerably evolved and are now multifaceted. With the recent adoption of its *Climate Change Operational Framework 2017-2030*, and its commitment to achieve \$2 billion in adaptation financing by 2020, ADB has asserted its strong commitment to support developing member countries to achieve climate resilient development outcomes. This initiative further underscores ADB's commitment to provide appropriate and relevant knowledge to its developing member countries enabling them to design responses to the emerging challenges from climate change. The report also highlights the premium ADB places on its partnerships with knowledge institutions such as this joint work with PIK.



Bambang Susantono

Vice-President for Knowledge Management
and Sustainable Development
Asian Development Bank



Professor Hans Joachim Schellnhuber CBE

Director, Potsdam Institute for Climate Impact Research
Professor for Theoretical Physics, University of Potsdam
Chair, German Advisory Council on Global Change

ACKNOWLEDGMENTS

This report has been written by a team of experts from the Potsdam Institute for Climate Impact Research (PIK) in collaboration with a team of experts from the Asian Development Bank (ADB).

The team of authors at PIK includes Kira Vinke, Hans Joachim Schellnhuber, Dim Coumou, Tobias Geiger, Nicole Glanemann, Veronika Huber, Jürgen Kropp, Steffen Kriewald, Jascha Lehmann, Anders Levermann, Anastasia Lobanova, Maria Knaus, Christian Otto, Christopher Reyer, Alexander Robinson, Diego Rybski, Jacob Schewe, Sven Willner, Michel Wortmann, Fang Zhao, and Bin Zhou.

The team of authors at ADB includes Benoit Laplante, Xianfu Lu, and Charles Rodgers. Benoit Laplante and Kira Vinke acted as the overall technical editors of the report.

The writing of this report would not have been possible without the contributions of numerous individuals. We are thankful for the research assistance and technical support of Matthias Büchner, Astrid Gläsel, Dennis Hof, Lennart Lagmöller, David Lowis, Sophia Rottmann, Lisa Murken, Martin Wodinski, Rexel Abrigo (Climate Change Officer (Adaptation), ADB), Kae Sugawara (editor), and Rommel Marilla (lay-out).

We are especially grateful to the following individuals for their review of an early version of the report: Akm Mahfuzzudin Ahmed (Advisor, Sustainable Development and Climate Change Department, ADB), Maria Pia Ancora (Climate Change Specialist, East Asia Department, ADB), Eduardo Banzon (Principal Health Specialist, Sustainable Development and Climate Change Department, ADB), Edimon Ginting (Director, Economic Analysis and Operational Support Division, Economic Research and Regional Cooperation Department, ADB), Richard Jones (United Kingdom Met Science Fellow, Met Office Hadley Centre), Soonman Kwon (Technical Advisor [Health], ADB), David Anthony Raitzer (Economist, Economic Research and Regional Cooperation Department, ADB), Jay Roop (Senior Natural Resource Management Specialist, Pacific Department, ADB), Jindra Nuella Samson (Senior Economics Officer, Economic Analysis and Operations Support Division, Economic Research and Regional Cooperation Department, ADB), Yasmin Siddiqi (Principal Water Resources Specialist, Sustainable Development and Climate Change Department, ADB), and Joel Smith (Principal Associate, Abt Associates).

We would like to sincerely thank Hans Joachim Schellnhuber (Director, PIK) and Preeti Bhandari (Director, Climate Change and Disaster Risk Management Division, Sustainable Development and Climate Change Department, ADB) for their overall guidance and direction.

TABLES, FIGURES, AND BOXES

TABLES

1.1	Population of the Urban Agglomerations with 5 Million Inhabitants or More in 2014	11
1.2	Share of Area and Population of Low-Elevation Coastal Zones in Selected Countries of Asia, 2000	11
1.3	Projected Population in Low-Elevation Coastal Zones and Flood Plains in Selected Countries of Asia	12
1.4	Countries with Sector Shares of Gross Domestic Product (2012)	13
1.5	Electricity Generation Mix, 2010	13
2.1	Projected Average Temperature Changes for the Land Area of Asia	21
2.2	Percentage of Land Area at Risk of Heat Extremes	24
2.3	Projected Contribution to Future Sea-Level Rise for 2100 Relative to the Reference Period 1986–2005	31
3.1	Relative Changes in Crop Yields under Climate Change in 2050 Relative to 2000 under the A1B Scenario in Selected Countries of the Pacific (Worse-Case Scenarios)	57
3.2	Dam Storage, Storage per Capita, and Storage as a Percentage of Renewable Water Resources	59
3.3	Projected Annual Morbidity and Mortality from Diarrhea by Selected Country (All Ages) under a High Emissions Scenario	65
3.4	Predicted Annual Morbidity and Mortality from Dengue and Malaria by Selected Country under a High Emissions Scenario	68
3.5	Recommendations to Address Climate Change Induced Migration	93

FIGURES

1.1	Number of Cities of Varying Size in Asia and the World—2014	10
2.1	Multimodel Average Temperature Anomaly in June—August	20
2.2	Temperature Projections for the Land Area of Asia	21
2.3	Projected Frequency of Heat Extremes	23
2.4	Projected Percentage of Land Area Affected by Heat Extremes	24
2.5	Projected Change in Precipitation	26

2.6	Reconstructed Sea-Level Rise over the Last 2,500 Years	28
2.7	Projected Total Anthropogenic Sea-Level Rise for the 21st Century	29
2.8	Sea-Level Contribution of the Large Ice Sheets	30
2.9	Coastal Regions Most Vulnerable to a Climate Change-Related Sea-Level Rise (Asia and the Pacific)	32
2.10	Tropical Cyclones Frequency in Asia and the Pacific	34
2.11	Projected Population of Asia and the Pacific at Risk Under Different Socioeconomic Scenarios	37
3.1	Estimated Future Annual Additional Deaths of Children Attributable to Climate Change	64
3.2	Estimated Future Annual Additional Deaths of Elderly Attributable to Climate Change	67
3.3	Estimated Future Annual Additional Deaths Attributable to Climate Change	67
3.4	Population Density in Asia	70
3.5	Heat Island Effect in Kochi (India) and Baguio City (Philippines)	71
3.6	Urban Heat Island Intensity in Selected Cities of Asia and the Pacific	72
3.7	Potential Impacts of Climate Change on Energy Insecurity	76
3.8	Possible Impacts of Climate Change-Related Resource Shortages on Rural and Urban Populations	79
3.9	Subregional Analysis of Climate Change-Related Migration	84
3.10	Bangladesh—Climate Impacts and Possible Migration Routes	85
3.11	Philippines—Climate Impacts and Possible Migration Routes	87
3.12	People’s Republic of China—Climate Impacts and Possible Migration Routes	88
3.13	Indus Delta—Climate Impacts and Possible Migration Routes	89
3.14	Tuvalu—Climate Impacts and Possible Migration Routes	91
3.15	Mekong Delta—Climate Impacts and Possible Migration Routes	92
3.16	Production Interdependencies Illustrated for India in 2011	97
3.17	Global Consumption Changes	98

BOXES

3.1	Pakistan Floods of 2010 and Diarrheal Diseases	63
3.2	Heat Wave 2015 in India	66
3.3	Large Outbreaks of Dengue in 2015/16 in South Asia and Southeast Asia	69
3.4	Estimating Production Shortage Interdependencies	96

ABBREVIATIONS

°C	degrees Celsius	km/h	kilometer per hour
ADB	Asian Development Bank	km ²	square kilometer
AR5	Fifth Assessment Report of the IPCC	Lao PDR	Lao People's Democratic Republic
ADB	Asian Development Bank	LECZ	low-elevation coastal zones
CMIP5	Coupled Model Intercomparison Project Phase 5	m	meter
CO ₂	carbon dioxide	mm/year	millimeter per year
DEMs	digital elevation models	NIO	North Indian Ocean
DIVA	Dynamic and Interactive Vulnerability Assessment	PDO	Pacific Decadal Oscillation
DJF	December–January–February	PRC	People's Republic of China
ENSO	El Niño Southern Oscillation	RCP	Representative Concentration Pathway
GCM	General Circulation Model	SIO	Southern Indian Ocean
GDP	gross domestic product	SLR	sea-level rise
GHG	greenhouse gas	SPO	Southern Pacific Ocean
GLOF	glacial lake outburst flood	SRTM	Shuttle Radar Topography Mission
IAM	integrated assessment model	SSP	shared socioeconomic pathway
ICIMOD	International Centre for Integrated Mountain Development	SST	sea surface temperature
IPCC	Intergovernmental Panel on Climate Change	UHI	urban heat island
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project	UNFCCC	United Nations Framework Convention on Climate Change
JJA	June–July–August	WHO	World Health Organization
		WMO	World Meteorological Organization
		WPO	Western Pacific Ocean

EXECUTIVE SUMMARY

The Asia and Pacific region is extremely vulnerable to the impacts of climate change. Unabated warming could significantly undo previous achievements of economic development and improvements of living standards. At the same time, the region has both the economic capacity and weight of influence to change the present fossil-fuel based development pathway and curb global emissions. This report sheds light on the regional implications of the latest projections of changes in climate conditions over Asia and the Pacific. The assessment concludes that, even under the Paris consensus scenario in which global warming is limited to 1.5°C to 2°C above preindustrial levels, some of the land area, ecosystems, and socioeconomic sectors will be significantly affected by climate change impacts, to which policy makers and the investment community need to adapt to. However, under a Business-As-Usual (BAU) scenario, which will cause a global mean temperature rise of over 4°C by the end of this century, the possibilities for adaptation are drastically reduced. Among others, climate change impacts such as the deterioration of the Asian “water towers”, prolonged heat waves, coastal sea-level rise and changes in rainfall patterns could disrupt ecosystem services and lead to severe effects on livelihoods which in turn would affect human health, migration dynamics and the potential for conflicts. This assessment also underlines that, for many areas vital to the region’s economy, research on the effects of climate change is still lacking.

Temperature Change

With unabated climate change, mean summer temperatures are expected to increase by more than 6°C above preindustrial levels by the end of the 21st century over some parts of the land of Asia. Locally, temperature changes can deviate significantly from mean changes in the global or regional temperature. Climate model projections indicate stronger summertime warming over higher latitudes in Asia where the temperature increase may reach up to 8°C.

Heat Extremes

The occurrence of heat extremes is more heterogeneously spread over the land mass of the region. Under the BAU scenario, summer temperatures considered unusual under current climate conditions might become the new norm from 2070 onward. Some areas, particularly in Southeast Asia, could enter into entirely new climate regimes due to frequent occurrence of unprecedented heat extremes.

Limiting global warming to 2°C would significantly lower the risk of severe heat extremes. Moreover, keeping global warming below 1.5°C would halve the percentage of Asian land areas expected to experience heat extremes compared to a 2°C warmer world.

Precipitation

Climate models project a general upward trend in annual mean precipitation over most of the land of the region toward the end of the 21st century. However, the magnitude of change is much larger for the BAU scenario than for the Paris consensus scenario. Both observations and state-of-the-art climate model projections show a pronounced increase in

the frequency and intensity of heavy rainfall events, particularly over Southeast Asia, which may thus face more severe flooding if the global temperature continues to rise.

Sea-Level Rise

If the Paris Agreement is fully implemented, sea-level rise may be limited to 0.65 meters within the course of this century. Under the BAU scenario however, sea level may rise by 1.4 meters. Under both scenarios, sea level will continue to rise for many centuries to come. For every degree of global warming, the world is committed to an eventual sea-level rise in excess of 2.3 meters. Thus, even if the 2°C guardrail were to be respected, sea level would eventually rise by more than 5 meters over centuries and millennia.

Glaciers and Rivers

The glaciers across the High Mountain regions of Asia have shown measurable signs of recession. However, changes are highly heterogeneous. Available climate change impact assessments have shown an increase of both the risk of flooding and water shortages, as the natural storage capacities of glaciers diminish while glacial lake outburst floods become more likely. As a result, the dependency on rainwater increases.

While flooding risks will increase in the Asian monsoon region due to heavy precipitation and runoff, it is also very likely that the region will face water shortages due not only to projected changes in climate but also to growing water demand from rapid population and economic growth. Options to cope with water scarcity may include integrated river basin management, adaptive management of old reservoirs, construction of new reservoirs, and techniques for efficient water use such as rainwater harvesting and water reuse.

Tropical Cyclones

Tropical cyclone activity by itself is driven by large internal variability that potentially prohibits the attribution of projected losses to different levels of global warming. Therefore, a quantification of the effect different degrees of global warming could have on tropical cyclone impacts for the Asia and Pacific region remains challenging. Nevertheless, there is a projected upward trend in damages under a warming climate. However, due to increasing tropical cyclone strength with rising global mean temperature and taking into account the co-hazard of sea level rise, it is likely that a BAU climate development will lead to significantly higher losses than those under the climate associated with the Paris consensus climate scenario.

Agriculture

Climate change poses large, but regionally differing, threats to agriculture and food security in Asia through higher temperatures, drier conditions, sea-level rise, and flooding. Major uncertainties pertaining to the extent of the threat relate to the potential effects of carbon dioxide fertilization.

Both biophysical climate impacts and ensuing impacts on development are likely to be substantial in the region. Currently, declining soil productivity, groundwater depletion, and declining water availability, as well as increased pest incidence and salinity, threaten food security in the region.

Fisheries and Reef Ecosystems

Under the BAU scenario, all coral reef systems are projected to collapse due to mass bleaching. Recent analyses show that even with global warming limited to 2°C, almost all coral reefs are projected to experience severe bleaching, resulting in massive dieback. This would have severe consequences for coastal livelihoods such as fisheries and tourism, as fish stocks could be greatly reduced with impaired reef ecosystems. Limiting global warming to 1.5°C could prevent the complete loss of corals.

Security

Energy resources, natural resources and poverty are significant variables in the generation of conflicts. Their vulnerability to climate change impacts is likely to be a future driver of instabilities. The threat of energy insecurity emerges from potential grid infrastructure failure, a continued reliance on unsustainable fossil fuels and energy imports, intermittent performance of hydropower plants as a result of uncertain water discharges, and reduced capacities of thermal power plants as a result of an increasing scarcity of cooling water. Investments in fossil fuel production like coal-fired power plants could turn into stranded assets as renewable energy sources achieve market dominance. As energy demand in the Asian region rises, yet supply becomes insecure, conflicts are a potential outcome. All these factors considered, climate change poses significant challenges to human security in Asia in the coming decades. Policy makers and investors have the chance to step in and manage risk factors by creating spaces for regional to local mitigation and adaptation strategies in order to prevent potential escalation of conflicts.

Migration

Rising temperatures, reductions in water availability, as well as an increasing frequency and severity of disaster events are already causing human displacement—a trend that could be aggravated by future climate impacts. The depreciation and degradation of natural resources through climate change threatens to lead to an increase in rural poverty and migration to cities, which will in turn add to the growth of informal settlements. Cities, as a result, will be vulnerable to both global climate events, due to their reliance on global supply chains, and local disasters, due to the vulnerability of the makeshift settlements that migrants often inhabit in urban slums. While a 2°C temperature rise will already lead to moderate risks in some regions, a 4°C increase could trigger severe disruptions of ecosystem services vital to the Asian economy. This could lead to humanitarian disasters in many nations and result in unmanageable migration surges, or locked-in populations.

Cities

The challenges confronting the fast-growing Asian cities with regard to climate change are twofold: (i) many of them will be affected by the consequences of global warming, and (ii) they are part of the problem, as they emit a disproportionate amount of greenhouse gases largely due to the concentration of human activities in urban areas. Already today, the number of hot days in cities is twice as high as in the hinterland. By the end of the 21st century, this number could be 10 times higher.

Supply Chains

Disruption in supply chains caused by extreme weather events can propagate through the globalized trade network. Since Asia's industries are particularly highly interlinked, extreme events in Asia can have strong repercussions within the region as well as in the rest of the world. Conversely, Asia's production and consumption can suffer from events outside the region.

Tailored adaptation plans need to be developed by both private and public sectors to enhance the resilience to such shock cascades. These plans also necessitate cooperation among many countries in Asia. Further research on adaptation measures to be taken by different stakeholders is critically important to support such collective action.

Health

Climate change poses a significant risk to human health in Asia and the Pacific, threatening to reverse many of the health improvements that have been achieved in the past decades. The World Health Organization recently estimated approximately 16,000 annual deaths among children below 15 years of age related to, and 26,000 annual deaths in small children below 5 years of age related to undernutrition (stunting), attributable to climate change in the 2030s across the Asia and Pacific region. These estimates would be 8,000 for diarrheal diseases and 21,000 for undernutrition (stunting), respectively, in the 2050s. According to the same assessment, regional heat-related deaths among the elderly (over 65 years) are thought to increase by approximately 20,000 cases due to climate change by the 2030s and approximately

52,000 cases by the 2050s. Attributable mortality related to vector-borne diseases (malaria and dengue) are estimated to be on the order of 3,000 annual deaths in the 2030s and 10,000 annual deaths in the 2050s. Yet, these estimates only represent a small portion of the climate impacts on human health to be expected because many known climate-sensitive health outcomes have so far been omitted from existing analysis.

The findings of this report highlight the severity of consequences of unabated climate change in Asia. While the climate impacts under the Paris consensus scenario of a temperature increase between 1.5°C and 2°C will pose significant challenges to the region, it is clear that the BAU scenario would render efforts to adapt Asia's population and economy to this new climatic regime ineffective. Because the coming decade is crucial for implementing adequate mitigation measures to deliver on the Paris Agreement, investments leading to a rapid decarbonization of the Asian economy have to receive high priority. At the same time, adaptation measures to protect the most vulnerable populations of the region need to be implemented. While pilot projects of renewable energy and technological innovation in urban infrastructure and transport need to spearhead this transformation, the consideration of mitigation and adaptation has to be mainstreamed into macro-level regional development strategies and micro-level project planning in all sectors. This would not only contribute to managing climate change risks for Asia and the Pacific, but also provide opportunities for directing regional economies toward a low-carbon and climate-resilient pathway.



INTRODUCTION



Mean global surface temperature has risen by approximately 1.1°C since the beginning of the Industrial Revolution. In a press communiqué published on 18 January 2017, the World Meteorological Organization (WMO) confirmed that 2016 was the warmest year since instrumental weather measurements began in 1880—directly following the previous record years 2014 and 2015 (WMO 2016). Indeed, 16 of the 17 warmest years registered in modern times have occurred since 2001. As pointed out by the Intergovernmental Panel on Climate Change (IPCC), this warming is largely the result of greenhouse gas emissions from human activities into the atmosphere (IPCC 2014). Ice caps are melting, oceans are acidifying, and the steadily rising sea level together with ever stronger typhoons are posing existential threats to the coastal regions of Asia and the Pacific (IPCC 2014).

The last decade has been characterized by a surge in weather extremes (Rahmstorf and Coumou 2011; Coumou and Rahmstorf 2012). Robust evidence exists for a significant increase in the occurrence of heat waves and heavy rainfall events at the global scale (Coumou, Robinson, and Rahmstorf 2013; Lehmann, Coumou, and Frieler 2015). This has also been reflected in an exceptional number of unprecedented climate extremes over the Asian continent. For example, in 2010, Pakistan experienced the worst flooding in the country's history. The unusually heavy monsoon rainfall led to approximately 3,000 deaths, left several million people homeless, and affected about half a million hectares of agricultural land (Hong et al. 2011). This inundation event was related to the unusual behavior of the jet stream, a band of strong westerly winds at an altitude of 10–12 kilometers. In late July and early August 2010, the jet stream was forced farther south than usual, dragging moist air to northern Pakistan where it met the advanced tropical monsoon front. This led to the devastating flooding of the Indus River basin. Even further south, India suffered severe heat waves in both 2015 and 2016. Among other factors, a weak premonsoon season with little rainfall leading to dry soils and a strong El Niño phase contributed to this heat wave with local temperatures rising well above 50°C. With increasing global warming, such types of heat extremes are expected to intensify and become more frequent in the future—if not the new normal.

Higher ocean surface temperatures will increase the intensity of typhoons (Elsner, Kossin, and Jagger 2008; Knutson et al. 2010; Holland and Bruyère 2014; Kang and Elsner 2015). In November 2013, the Philippines was hit by typhoon Haiyan, the strongest storm ever recorded to strike land with 1-minute sustained wind gusts of 315 kilometers per hour (km/h). It has been shown that a concurrence of high sea surface temperatures, above normal ocean heat content, and elevated sea level considerably exacerbated the strength of the associated devastating storm surge (Trenberth, Fasullo, and Shepherd 2015). Ocean warming is severely impacting coral reefs. In combination with ocean acidification caused by the increasing atmospheric concentration of carbon dioxide, large fractions of coral ecosystems are expected to face extinction even at 1.5°C global warming (Frieler et al. 2012). Coral bleaching has already been observed in the region of the Coral Triangle.¹ This region contains a third of the world's remaining tropical reefs and is recognized as the reef community with the largest biodiversity. Studies have shown that the most extreme El Niño and La Niña events will occur more often in a scenario with unabated greenhouse gas emissions (Cai et al. 2015). This would have severe consequences for precipitation and temperature extremes over Asia, where the weather is strongly influenced by the monsoon system dynamics and the El Niño–Southern Oscillation phenomenon. In fact, these phenomena are interacting, yet the precise mechanisms involved still need to be revealed by science.

The Asia and Pacific region is thus exceptionally exposed to climate change impacts. Home to the majority of the world's poor, the population of the region is also particularly vulnerable to those impacts. Countries of the region top the list of those most affected by extreme weather events. Between 1996 and 2015, six of the world's ten most affected countries by those events (in terms of both fatalities and economic losses) were in Asia (Myanmar, the Philippines, Bangladesh, Viet Nam, Pakistan, and Thailand) (Kreft, Eckstein, and Melchior 2016). Studies have projected significant losses of gross domestic product throughout the region as a result of climate change (ADB 2009a, 2013a, 2013b, 2014). Subsistence-oriented communities around Asia and the Pacific are already observing

¹ The Coral Triangle is located along the equator where the Pacific Ocean meets the Indian Ocean covering the marine waters of Indonesia, Malaysia, Papua New Guinea, the Philippines, and Solomon Islands.

clear-cut impacts of anthropogenic climate change (Savo et al. 2016).

At the 2015 United Nations Climate Change Conference (COP21) in Paris, leaders from 195 nations committed to limit global warming to well below 2.0°C and even to muster strong efforts for limiting the planetary temperature increase to 1.5°C. However, current emissions reduction pledges by Parties to the United Nations Framework Convention on Climate Change (UNFCCC) would most likely result in a global mean temperature increase of approximately 2.7°C above preindustrial levels by 2100 (Gütschow et al. 2015).² In view of the concrete measures implemented so far, the planet is on a path to around 3.0°C of warming by the end of the century, even assuming substantial emissions reductions in the future. If nations do not go well beyond their Paris pledges, the world's carbon budget in line with the Paris Agreement will be exhausted as early as 2032 (Tollefson 2015). In most scenarios, limiting the global temperature increase to 2.0°C requires that world emissions peak around 2020 and then reach negative net emissions in the second half of the century. This will require significant and rapid technological and transformational changes (Schellnhuber, Rahmstorf, and Winkelmann 2016; Schleussner et al. 2016).

Regardless of what will be achieved on the mitigation side, a planetary warming of 1.5°C–2.0°C represents one of (if not) the greatest management challenges of the 21st century faced by humankind in general, and by the people of Asia and the Pacific in particular. This challenge must be tackled in spite of the fact that the level of public concern about climate change is lower in Asia than in most other regions (Wike 2016).

Despite the rapidly emerging risks, Asia's emissions of greenhouse gases are rising, not only creating global negative externalities but also immediately impacting the region's own local populations in the form of hazardous levels of air pollution. Poor air quality affects the daily lives of citizens of Bangkok, Beijing, Delhi, Karachi, Patna, and many other settlements. Every year of the last decade, there have been 3.3 million deaths on average from the

effects of outdoor air pollution—more fatalities than from HIV and malaria combined (Lelieveld et al. 2015). The top four countries in which these deaths occur are in Asia: the People's Republic of China (PRC), India, Pakistan, and Bangladesh. Furthermore, many of the great Asian cities contain vast informal settlements extremely vulnerable to changes in the environment. Prolonged heat waves, extreme precipitation, and cyclonic events can place insurmountable burdens on poor populations that have no resources to adapt to these changes (German Advisory Council on Global Change 2016). Moreover, many of the region's slums are expected to grow without foreseeable improvements in their infrastructures. This trend may be aggravated by climate change impacts on agriculture, annihilating many of the rural population's livelihoods and precipitating temporary or permanent migration to nearby cities and beyond.

Asia is one of the keys to achieving global development and human progress within planetary boundaries (Rockström et al. 2009). The region will be either transformed by imposed driving forces such as unbridled climate change and transboundary migration, or it will help deliberately shape the sustainability transformation domestically and worldwide. The necessary efforts will mainly revolve around the triangle formed by innovation, infrastructure, and investment. Innovation for sustainable development requires new formats and partnerships, not least between governments, academia, and private businesses. Infrastructure has to be built and refurbished in a way that both avoids a lock-in to unsustainable development paths and is resilient to the projected impacts of climate change. Finally, existing investment institutions including development partners must be invigorated and recalibrated for the unprecedented challenges faced by the region in the next decades.

This report offers an overview of the projected changes in climate in the Asia and Pacific region based on the best available scientific evidence, and of the various human dimensions of these impacts. Whereas the focus of the assessment lies on the implications of the global warming target under the Paris Agreement (1.5°C–2.0°C increase

² These pledges (to mitigate emissions of greenhouse gases) are known as *intended nationally determined contributions* or INDCs. At the time of this writing, 185 countries have submitted pledges. These countries represent approximately 97% of global greenhouse gas emissions.

above preindustrial levels), references are also made to the potential impacts under a business-as-usual scenario (4.0°C increase above preindustrial levels by the end of the century), highlighting the dire consequences of a failure to deliver on the Paris Agreement. This report is meant to serve, in particular, regional policy makers, industries, and the investment community, providing them with a systemic overview of the various consequences arising from climate change in Asia and the Pacific. The assessment especially emphasizes the related challenges for economic development and the risks of exacerbated rural–urban migration and civil conflict in a drastically changing environment. Building on the latest relevant expert literature, the report attempts to inform and incentivize transformative change in the region. Also, recommendations are made on where further research is urgently needed.

Part 1 provides a brief overview of Asia and the Pacific with a focus on the region’s key characteristics of relevance to

the understanding of the climate change challenges and opportunities: its geography, its people, and its economy.

Part 2 focuses on the combined and interacting physical and biophysical climate change impacts, covering future changes in temperature and heat extremes (2.1), precipitation (2.2), sea-level rise (2.3), and tropical storms (2.4). Changes in hydrology (2.5) and the impacts of climate change on flooding risks in Asia’s river basins (2.6) are also discussed.

Part 3 shows how these changes affect human systems, elaborating on agriculture and marine ecosystems (3.1), human health (3.2), urban areas (3.3), and security (3.4). It also examines the effects on the regional economy through migration (3.5) and Asia’s trade networks (3.6). These insights create a unique basis to guide Asia and the Pacific in its pursuit of climate resilience.



ASIA AND THE PACIFIC
AT A GLANCE

1



Climate change is a key determinant of the future of the population of the Asia and Pacific region and of its development. This brief section aims to highlight features of the region relevant to the interaction of physical climate impacts with human systems. These characteristics pertain to the region's geography, from mountains to sea, and from tropical lush to desert; its people, urbanized and coastal; and its economy—both industrialized and rural. This section provides the background and rationale for the study of the selected impacts of climate change presented in Part 3.

1.1 Asia and the Pacific: Its Geography

Continental Asia is the largest land mass on Earth, and the Asia and Pacific region is one of the most diverse places in the world with regard to both physical and social geography. It is bounded to the north by the Arctic Ocean, to the east by the Pacific Ocean, and to the south by the Indian Ocean.

The 48 regional members of the Asian Development Bank (ADB) are located in highly distinct climatic zones, containing humid subtropical, cold arid, and subarctic East Asia; cold arid and semiarid Central Asia; hot humid tropical and subtropical, and hot arid South Asia; and the tropical Southeast Asia (Peel, Finlayson, and McMahon 2007). Specific climatic features are influenced by the monsoon circulation dominating large areas of southern and eastern Asia (Rohli and Vega 2012). Other areas, including the Southern Indian Ocean and the Southern Pacific Ocean, are heavily influenced by tropical cyclone activity. The region's biomes also differ vastly, ranging from rainforests, savannas, and deserts to alpines, grasslands, and temperate deciduous forests (de Blij, Muller, and Williams 2004). Moreover, the continent also contains many of the world's largest mountains, plateaus, steppes, deserts, rivers, lakes, and deltas.

The Tibetan Plateau is a unique feature of the region and of the world. With an average elevation exceeding 4,500 meters and an area of 2.5 million square kilometers (km²), it is the world's largest and highest plateau. It covers most of the Tibet Autonomous Region and Qinghai Province

in the PRC as well as parts of India. It is most famously associated with the Himalayan mountain range separating the Indian subcontinent from the Tibetan Plateau and the rest of Asia. This range contains nine of the ten highest peaks in the world, among which the highest peak on Earth, and the third-largest deposit of ice and snow in the world, after Antarctica and the Arctic. The Himalayan constitutes a major source of water for Asia's largest rivers, including the Indus, the Yangtze, and the Ganges–Brahmaputra (Pomeranz 2013) on which approximately 1.3 billion people depend for their water supply (Blondel 2012; Pomeranz 2013). Simultaneously, Central Asia and parts of East Asia are dominated by a steppe landscape, with Mongolia specifically divided into the mountain forest steppe, the arid steppe, and the desert steppe, including the Gobi Desert and the Taklimakan Desert, among the largest in the world (Man 1999; Sun and Liu 2006).

The Yangtze is the longest river in Asia and the third-longest in the world, moving east from the glaciers of the Tibetan Plateau to the river's outlet on the East China Sea. It is considered the lifeblood of the PRC as it irrigates 20% of the country's land area. The river as well as the goods and services that its ecosystem produces form the basis of vital parts of the PRC's economy. Similarly, the Mekong River running from the Tibetan Plateau through the PRC, Myanmar, the Lao People's Democratic Republic (Lao PDR), Thailand, Cambodia, and Viet Nam; the Indus River flowing mainly through Pakistan, but also through India and the western Tibet Autonomous Region; and the Ganges River flowing through India and Bangladesh all support ecosystems of temperate forests, plains, and arid countryside and are key contributors to the region's livelihoods and development (Albinia 2010).

In addition to mountains and rivers, the Asia and Pacific region also contains numerous large river deltas including those of the Yellow River, the Yangtze, the Pearl River, the Red River, the Mekong, the Chao Phraya, the Irrawaddy, the Indus, and the Ganges, the world's largest delta. These are among the most fertile deltas in the world providing home and livelihoods to hundreds of millions of people of the region. Simultaneously, river deltas are among the geographical assets of the world most vulnerable to the impacts of climate change (Van Driel et al. 2015).

The 14 Pacific developing member countries of ADB,¹ while varying in terms of their culture and economic achievements, share a situation characterized by development constraints due to their limited country and population sizes, their limited resource endowments, as well as their remoteness, causing significant exposure to external economic shocks (ADB 2009b). These are conducive to a fragile and vulnerable development environment. This environment is particularly exposed and vulnerable to changes in oceanic and associated atmospheric conditions. The projected rise in sea levels represents a significant threat to the long-term viability of many islands of the Pacific.

1.2 Asia and the Pacific: Its People

The people of Asia are characterized by two important features, key to understanding the region's exposure and vulnerability to climate change impacts: Asia's population is increasingly urbanized and coastal.

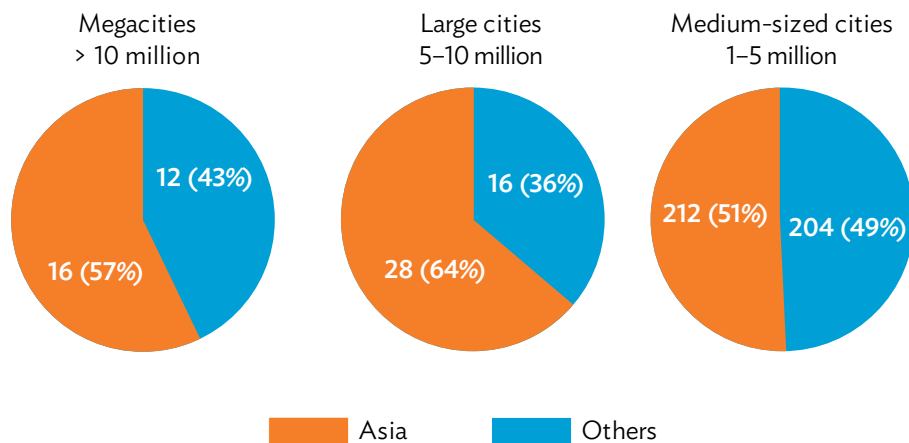
The total population of the developing member countries of ADB increased from approximately 1.23 billion in 1950 to 3.90 billion in 2015. This number is projected to range

between 4.14 billion (low growth) and 5.19 billion (high growth) in 2050 (UN DESA 2015).

Perhaps even more importantly, Asia's urban population has increased significantly over the last decades from approximately 20% of the population being urbanized in 1950 to approximately 50% in 2016. This percentage is expected to reach approximately 64% in 2050. In absolute terms, Asia's urban population, estimated at approximately 1.689 billion in 2015, is projected to increase to 2.256 billion in 2030 and reach 2.753 billion in 2050. One billion more people of the region are expected to live in Asia's urban areas in 2050 than there are today (UN DESA 2014). This urbanization dynamic already poses significant challenges to city development and administration. In many cities, the urban population increase outpaces the growth in the urban labor market which can further the formation of informal settlements (German Advisory Council on Global Change 2016).

The Asia and Pacific region includes a large number of the largest cities on Earth. In 2014, Asia accommodated 16 of the 28 megacities (with more than 10 million inhabitants) of the world and 28 of the 44 large cities (with 5 million–10 million inhabitants) (Figure 1.1).

Figure 1.1: Number of Cities of Varying Size in Asia and the World—2014



Source: United Nations. 2014. *World Urbanization Prospects of the United Nations*. 2014 revision. New York: United Nations.

¹ Comprising the Cook Islands, Fiji, Kiribati, Marshall Islands, the Federated States of Micronesia, Nauru, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga, Tuvalu, and Vanuatu.

Table 1.1: Population of the Urban Agglomerations with 5 Million Inhabitants or More in 2014
(million)

	1990	2014	2030 (projected)
Total 71 of the world ^a	433.469	753.420	962.487
Total 33 of Asia ^b	151.046	348.714	483.774
Asia's share (%)	34.8	46.2	50.2

^a Total population of the 71 urban agglomerations of the world with 5 million people or more in 2014.

^b Total population of the 33 urban agglomerations with 5 million or more of Asia and the Pacific in 2014.

Source: United Nations Department of Economic and Social Affairs Population Division. 2014. *World Urbanization Prospects*. New York. United Nations.

Asia accounts for 33 of all 71 urban agglomerations with more than 5 million inhabitants of the world (as of 1 July 2014). These 33 urban agglomerations had a total population of approximately 348.7 million in 2014. Their population is projected to reach 483.7 billion in 2030, an increase of approximately 40% over a 15-year period (Table 1.1). By 2030, Asia is anticipated to host eight more megacities, four of which in India: Chennai, Bangalore, Hyderabad, and Ahmadabad.

The significance of this key characteristic of the Asia and Pacific region is reflected in Part 3 in the context of the discussion of the heat island effect associated with the projected increase in temperature.

In addition to becoming increasingly urbanized, a large share of the region's population and a large share of the region's urban agglomerations are located within a short distance of the coast of the region. Throughout the region, coastal population growth is far higher than national growth. For example, McGranahan, Balk, and Anderson (2007) estimate that population growth in the low-elevation coastal zones (LECZs) of the PRC and Bangladesh grew at approximately twice the rate of the national growth between 1990 and 2000. In many countries of Asia and the Pacific, the share of the national population located in such zones is typically much larger than the relative area of the zones. For example, in the

Table 1.2: Share of Area and Population of Low-Elevation Coastal Zones in Selected Countries of Asia, 2000 (%)

Country	LECZ Area as Share of Total Country Area	LECZ Population as Share of Total Country Population
Bangladesh	40.2	48.7
Cambodia	7.5	25.7
PRC	2.0	11.3
India	2.6	6.1
Indonesia	9.1	18.4
Myanmar	7.3	27.8
Pakistan	2.9	3.2
Philippines	6.8	16.7
Thailand	6.8	26.0
Viet Nam	20.2	54.7

LECZ = low-elevation coastal zone, PRC = People's Republic of China.

Source: Adapted from B. Neumann et al. 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding—A Global Assessment. *PLOS One*. 10 (6). e0131375.

PRC and India, low-elevation coastal zones represent less than 3% of their total land area. However, approximately 11.3% and 6.1% of the total population of these countries, respectively, is located in such zones (Table 1.2). More than 50% of Viet Nam's population lives in approximately 20% of the land occupied by LECZs. In the baseline year 2000, approximately 403 million people were located in the LECZs of the 10 countries presented in Table 1.2.

Given that most of Asia's economic centers are located on coastlines, coastal populations are expected to increase significantly and approximately double in countries such as Bangladesh, India, the Philippines and Viet Nam by 2060 (Table 1.3).

These coastal urban areas are strongly exposed to the projected predicaments associated with climate change. In a study of exposed assets and population in 136 port cities of the world, Hallegatte et al. (2013) estimate the bulk of the projected coastal flood damage in 2050 to take place in East Asia and South Asia.

Table 1.3: Projected Population in Low-Elevation Coastal Zones and Flood Plains in Selected Countries of Asia (million)

Country	LECZ Population		Population in 1-in-100-Year Flood Plains	
	2000	2060 (projected)	2000	2060 (projected)
Bangladesh	63.1	109.5	6.0	12.4
Cambodia	3.2	6.0	0.6	1.4
PRC	144.0	244.8	56.0	103.4
India	63.9	216.4	17.1	63.6
Indonesia	39.3	93.7	5.4	14.5
Myanmar	12.5	22.8	3.1	6.3
Pakistan	4.6	30.1	0.7	5.7
Philippines	13.0	34.9	2.0	5.8
Thailand	16.4	36.8	3.5	9.1
Viet Nam	43.1	80.4	26.3	50.6

LECZ = low-elevation coastal zone, PRC = People's Republic of China.

Source: Adapted from B. Neumann et al. 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding – A Global Assessment. *PLOS One*. 10 (6). e0131375.

1.3 Asia and the Pacific: Its Economy

A key economic development of the last decades has been the rapid increase in income per capita in the Asia and Pacific region. When measured in purchasing power parity terms, average income per capita in the region increased from \$1,474 in 1980 to approximately \$5,900 in 2000 and to \$12,600 in 2015 (based on statistics available in IMF 2016). Over a period of 25 years, average income per capita increased approximately tenfold, with rapid industrialization fueling this increase. At the same time, economic inequality has been widening and the creation of opportunities and stable incomes for the poor remains a significant challenge throughout the region (Zhuang, Kanbur, and Maligalig 2014).

In the course of the economic development of the region the structure of the economy has also changed. In many countries, the service sector now contributes more than 50% of gross domestic product (GDP) and industry contributes more than 30% of GDP (Table 1.4). The agriculture sector has seen the share of its contribution to GDP decline over the last decades. In 2015, agriculture contributed approximately 17.5% of the region's GDP.

While the sector represents a declining share of economic activity when its contribution to GDP is used as an indicator of measure, approximately 2 billion people in the region continue to depend on agriculture for their livelihoods. Adverse disruptions of agricultural productivity could have devastating effects throughout the region, increasing poverty, reducing food security, and incentivizing large migratory movements to urban agglomerations. The performance of all sectors of the economy depend on a well-functioning trade and transport network.

Except for the nations of the Pacific, the rapidly growing and evolving economy of Asia is still heavily dependent on fossil sources of electricity generation including coal, oil, and natural gas, contributing to the greenhouse gas effect. In 2010, coal and oil alone accounted for approximately 72% of the total primary energy demand in the region (ADB and APEC 2015). Approximately 70% of the region's electricity generation originates from these three fossil fuel sources (Table 1.5). Hydropower generation accounts for the bulk of the remaining sources of electricity. This characteristic of Asia's energy sector combined with the region's rapid economic development explains for the most part the region's increasing share of global emissions of greenhouse gases in general, and of carbon dioxide in particular.

Table 1.4: Countries with Sector Shares of Gross Domestic Product (2012)

Countries Where Industry Represents More Than 30% of Nominal GDP	Countries Where Service Sector Represents More Than 50% of Nominal GDP
Azerbaijan, Bhutan, PRC, Indonesia, Lao PDR, Mongolia, Nauru, Papua New Guinea, Philippines, Sri Lanka, Thailand, Timor-Leste, Turkmenistan, Uzbekistan, Viet Nam	Afghanistan, Armenia, Bangladesh, PRC, Cook Islands, Fiji, Kazakhstan, Kiribati, Kyrgyz Republic, Maldives, Marshall Islands, Federated States of Micronesia, Mongolia, Nauru, Nepal, Pakistan, Palau, Philippines, Samoa, Sri Lanka, Thailand, Tonga, Tuvalu, Vanuatu

GDP = gross domestic product, Lao PDR = Lao People's Democratic Republic, PRC = People's Republic of China.

Source: Central Intelligence Agency. 2012. *The World Factbook: GDP-Composition, by Sector of Origin*. <https://www.cia.gov/library/publications/the-world-factbook/fields/2012.html>

Table 1.5: Electricity Generation Mix, 2010 (%)

	Coal	Oil	Natural Gas	Hydro	Nuclear	Others
Central and West Asia	22.3	11.3	34.5	29.9	1.9	0.0
East Asia	73.0	0.0	4.9	14.6	5.3	1.3
Pacific	0.0	43.6	14.7	33.4	0.0	8.3
South Asia	63.9	3.3	15.2	12.9	2.6	2.2
Southeast Asia	27.4	8.2	48.9	11.9	0.0	3.6
All Developing Member Countries	65.0	2.4	12.0	14.8	4.2	1.6

Source: Asian Development Bank (ADB) and Asia-Pacific Economic Cooperation (APEC). 2015. *Energy Outlook for Asia and the Pacific*. Manila: ADB.

Recent technological advancements along with declining prices for renewable energy and energy storage suggest that fossil-fuel dependence is declining. For example, Saxena et al. (2017) indicate that India would not have to build new coal fired power stations to meet future energy demand and suggest that the country could transition out of coal fired power plants by the middle of the century.

Moreover, existing sources of electricity generation in the Asia and Pacific region (except for renewable sources) demand vast quantities of cold water which may not be met as a result of the impacts of climate change. This may

lead to energy insecurity and stand in competition with the use of freshwater supplies for drinking and agricultural purposes. This outlook further incentivizes a transition towards renewable energy sources.

The geography, demographics, and economy of Asia and the Pacific as outlined above are key to understanding the significance of potential impacts of climate change to the region's human systems. Whereas Part 2 provides an overview of these projected physical impacts of climate change, Part 3 discusses their interactions with human systems in the Asia and Pacific region.

References—Introduction and Part 1

- Albinia, A. 2010. *Empires of the Indus: The Story of a River*. London: John Murray.
- Asian Development Bank (ADB). 2009a. *The Economics of Climate Change in Southeast Asia: A Regional Review*. Manila.
- . 2009b. *The Pacific Approach 2010–2014*. Manila.
- . 2013a. *The Economics of Climate Change in the Pacific*. Manila.
- . 2013b. *Economics of Climate Change in East Asia*. Manila.
- . 2014. *Assessing the Costs of Climate Change and Adaptation in South Asia*. Manila.
- Asian Development Bank and Asia-Pacific Economic Cooperation (APEC). 2015. *Energy Outlook for Asia and the Pacific*. Manila: ADB.
- Blondel, A. 2012. *Climate Change Fuelling Resource-Based Conflicts in the Asia-Pacific*. Asia-Pacific Human Development Report Background Papers Series 2012/12.
- Cai, W., et al. 2015. ENSO and Greenhouse Warming. *Nature Climate Change*. 5. pp. 849–859.
- Coumou, D., and S. Rahmstorf. 2012. A Decade of Weather Extremes. *Nature Climate Change*. 2. pp. 491–496.
- Coumou, D., A. Robinson, and S. Rahmstorf. 2013. Global Increase in Record-Breaking Monthly-Mean Temperatures. *Climatic Change*. 118. pp. 771–782.
- de Blij, H. J., P. O. Muller, and R. S. Williams. 2004. *Physical Geography of the Global Environment*. Oxford, UK: Oxford University Press.
- Elsner, J. B., J. P. Kossin, and T. H. Jagger. 2008. The Increasing Intensity of the Strongest Tropical Cyclones. *Nature*. 455. pp. 92–95.
- Frieler, K., et al. 2012. Limiting Global Warming to 2°C Is Unlikely to Save Most Coral Reefs. *Nature Climate Change*. 2. pp. 1–6.
- German Advisory Council on Global Change (WBGU). 2016. *Humanity on the Move: Unlocking the Transformative Power of Cities*. Berlin.
- Gütschow, J., et al. 2015. *INDCs Lower Projected Warming to 2.7°C: Significant Progress but Still above 2°C*. Climate Action Tracker Update.
- Hallegatte, S., et al. 2013. Future Flood Losses in Major Coastal Cities. *Nature Climate Change*. 3. pp. 802–806.
- Holland, G., and C. L. Bruyère. 2014. Recent Intense Hurricane Response to Global Climate Change. *Climate Dynamics*. 42. pp. 617–627.
- Hong, C. C., et al. 2011. Roles of European Blocking and Tropical–Extratropical Interaction in the 2010 Pakistan Flooding. *Geophysical Research Letters*. 38 (13).
- Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by Core Writing Team, R. K. Pachauri, and L. A. Meyer. Geneva, Switzerland.
- International Monetary Fund (IMF). 2016. *World Economic Outlook Database*. IMF: Washington, D.C.
- Kang, N.-Y., and J. B. Elsner. 2015. Trade-Off between Intensity and Frequency of Global Tropical Cyclones. *Nature Climate Change*. 5. pp. 661–664.
- Knutson, T. R., et al. 2010. Tropical Cyclones and Climate Change. *Nature Geoscience*. 3. pp. 157–163.
- Kreft, S., D. Eckstein, and I. Melchior. 2016. *Global Climate Risk Index 2017: Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2015 and 1996 to 2015*. Bonn: Germanwatch.
- Lehmann, J., D. Coumou, and K. Frieler. 2015. Increased Record-Breaking Precipitation Events under Global Warming. *Climatic Change*. 132. pp. 501–515.
- Lelieveld, J., et al. 2015. The Contribution of Outdoor Air Pollution Sources to Premature Mortality on a Global Scale. *Nature*. 525. pp. 367–371.
- Man, J. 1999. *Gobi: Tracking the Desert*. New Haven: Yale University Press.
- McGranahan, G., D. Balk, and B. Anderson. 2007. The Rising Tide: Assessing the Risks of Climate Change and Human Settlements in Low Elevation Coastal Zones. *Environment and Urbanization*. 19. pp. 17–37.
- Peel, M. C., B. L. Finlayson, and T. A. McMahon. 2007. Updated World Map of the Köppen–Geiger Climate Classification. *Hydrology and Earth System Sciences*. 11(5). pp. 1633–1644.
- Pomeranz, K. 2013. Asia’s Unstable Water Tower: The Politics, Economics, and Ecology of Himalayan Water Projects. *Asia Policy*. 16.
- Rahmstorf, S., and D. Coumou. 2011. Increase of Extreme Events in a Warming World. *Proceedings of the National Academy of Sciences*. 108. pp. 17905–17909.
- Rockström, J., et al. 2009. A Safe Operating Space for Humanity. *Nature*. 461. pp. 472–475.
- Rohli, R. V., and A. J. Vega. 2012. *Climatology*. Burlington, MA: Jones & Bartlett Learning.

- Savo, V., et al. 2016. Observations of Climate Change among Subsistence-Oriented Communities around the World. *Nature Climate Change*. 6. pp. 462–473.
- Saxena, A. K., et al. 2017. *Transitions in Indian Electricity Sector*. The Energy and Resources Institute: New Delhi.
- Schellnhuber, J., S. Rahmstorf, and R. Winkelmann. 2016. Why the Right Climate Target Was Agreed in Paris. *Nature Climate Change*. 6. pp. 649–653.
- Schleussner, C. F., et al. 2016. Science and Policy Characteristics of the Paris Agreement Temperature Goal. *Nature Climate Change*. 6. pp. 827–835.
- Sun, J., and T. Liu. 2006. The Age of the Taklimakan Desert. *Science*. 312(5780). p. 1621.
- Tollefson, J. 2015. The 2°C Dream. *Nature*. 527. pp. 436–438.
- Trenberth, K. E., J. T. Fasullo, and T. G. Shepherd. 2015. Attribution of Climate Extreme Events. *Nature Climate Change*. 5. pp. 725–730.
- United Nations Department of Economic and Social Affairs Population Division (UN DESA). 2014. *World Urbanization Prospects*. New York: United Nations.
- . 2015. *World Population Prospects: The 2015 Revision*. New York: United Nations.
- Van Driel, W., et al. 2015. *Vulnerability Assessment of Deltas in Transboundary River Basins*. Delta Alliance contribution to the Transboundary Water Assessment Program, River Basins Assessment. Delta Alliance Report 9. Delft, The Netherlands: Delta Alliance International, Wageningen.
- Wike, R. 2016. *What the World Thinks about Climate Change in 7 Charts*. Washington, DC: Pew Research Center.
- World Meteorological Organization (WMO). 2016. *WMO Confirms 2016 as Hottest Year on Record*. Press release.
- Zhuang, J., R. Kanbur, and D. Maligalig. 2014. Asia's Income Inequalities: Recent Trends. In R. Kanbur, C. Rhee, and J. Zhuang, eds. *Inequality in Asia and the Pacific: Trends, Drivers, and Policy Implications*. Manila and New York: Asian Development Bank and Routledge.



**CLIMATE CHANGE IN ASIA AND THE PACIFIC:
OBSERVATIONS AND PROJECTIONS**



Part 2 contains a review and discussion of the projected climate change in Asia in the 21st century based on current scientific literature. Global and regional warming will induce changes highly relevant to human and ecological well-being and economic development within the region. These include changes in sea level, precipitation patterns, the intensity of tropical cyclones, and changes in hydrology, including significant impacts on Asia’s critically important glacier—and snow—fed river systems and on flooding and drought.

All projected future climate changes embody assumptions about how society will act to reduce—or fail to reduce—greenhouse gas (GHG) emissions. These, in turn, reflect a wide range of potential decisions concerning technological and economic changes. To highlight the influence of these decisions on the subsequent magnitude and pace of climate change, two different scenarios are presented: the first is broadly consistent with efforts to limit 21st century warming to below 2°C, the target of the Paris consensus and the second with “business as usual.”¹

The low-emission scenario of the Representative Concentration Pathways (RCP2.6) presents a future in which GHG mitigation efforts are aggressive and begin early. It assumes the availability and effectiveness of technologies to reduce atmospheric carbon dioxide (CO₂) (negative emissions) such as carbon capture and storage. In RCP2.6, global annual CO₂ emissions peak around 2020 and decline substantially over the 21st century (Moss et al. 2010). In this report, RCP2.6 is used as a proxy for successful implementation of the Paris Agreement since under RCP2.6 global warming is expected to stay at or below 2°C above preindustrial levels with a probability greater than 67%.² The high-emission scenario RCP8.5 is used as a proxy for a future in which international cooperation on climate mitigation

fails and the world economy continues to emit GHG on a business-as-usual pathway. Under this scenario, CO₂ emissions increase until the end of the 21st century with global mean temperature expected to rise by around 4°C above preindustrial levels. In the following sections, the terms RCP2.6 and “Paris-consensus” scenario are used interchangeably, as are RCP8.5 and “business-as-usual” scenario.³

The discussion of primary impacts and hazards associated with climate change in Asia—tropical cyclones, sea-level rise, and changes in hydrology—will summarize studies embodying a wider range of climate scenarios and projections, not necessarily limited to Paris consensus and business as usual.

2.1 Changes in Temperatures and Heat Extremes

In the absence of strenuous efforts to reduce global GHG emissions, global average summer temperatures are expected to increase by more than 6°C above preindustrial levels by the end of the 21st century (IPCC 2013). Regional and local temperature changes can vary significantly from the global average. Climate model projections indicate that in Asia summertime warming is stronger over higher latitudes (IPCC 2013). This part presents projections of temperature conditions in Asia, as well as changes in the frequency of severe heat extremes.

The analysis focuses on changes in boreal summer (June–August) because the strongest impacts from temperature changes on society, primarily associated with agricultural losses, are expected during this season (Hansen, Sato, and Ruedy 2012; Coumou, Robinson, and Rahmstorf 2013).

¹ The most current global climate modeling efforts, conducted through the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor, Stouffer, and Meehl 2012), simulate the climate impacts of four scenarios called Representative Concentration Pathways (RCP; Moss et al. 2010) that refer to global energy imbalances (forcings) in watts per square meter by 2100 resulting from different GHG emissions pathways. The RCP scenarios were developed by the global climate science community to facilitate policy-relevant research into climate change, with results assessed in the Fifth Assessment Report (AR5) of the IPCC, released in 2013 (IPCC 2013).

² Not all model simulations assuming RCP2.6 result in temperature increases below 2°C.

³ The analyses of temperature and rainfall changes presented here are based on the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) database (Warszawski et al. 2014), which utilizes climate projections from a subset of the most recent (CMIP5) global climate modeling work. The model ensemble includes the general circulation (global climate) models HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M. The model output is bias-corrected against late 20th century observations (Hempel et al. 2013) to improve future projections.

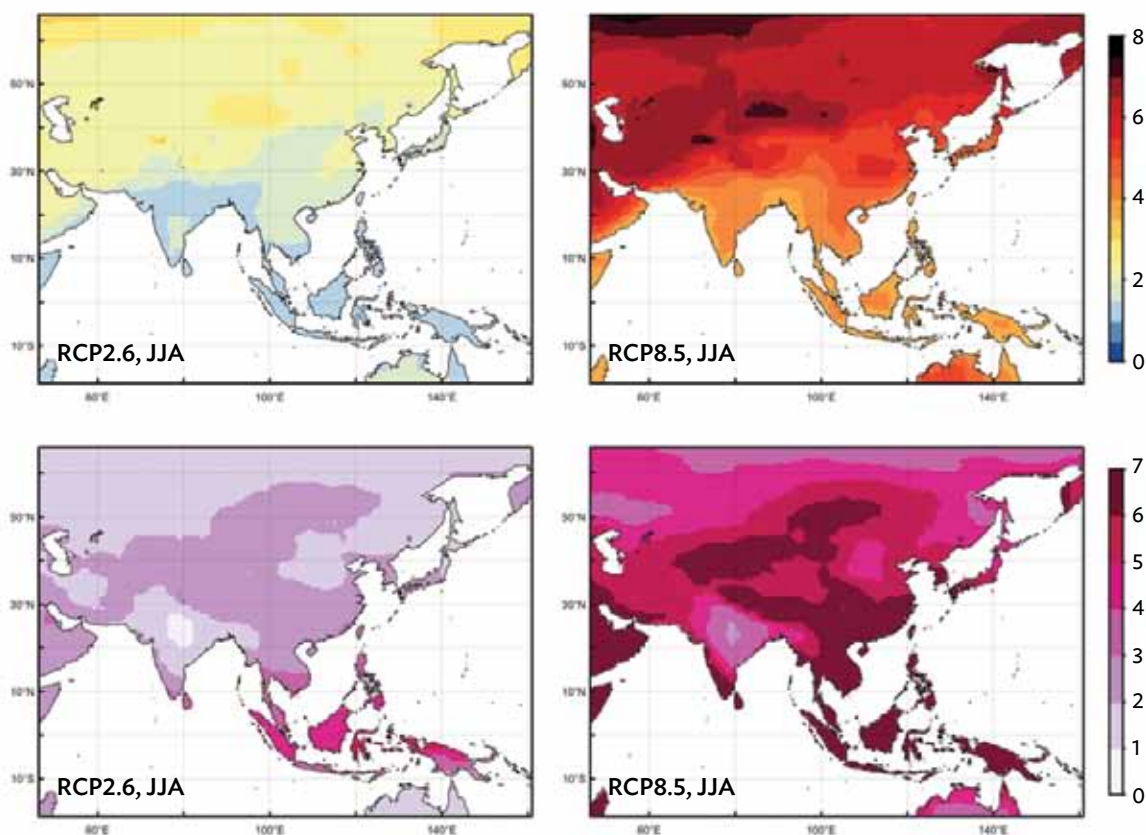
In the following discussion, all changes in temperature, including extremes, are reported for the seasonal average and with respect to the climatic baseline period 1951–1980.⁴

Projected Temperature Changes

Under the Paris-consensus scenario (RCP2.6), summer warming averaged over all continental land areas depicted in Figure 2.1 is projected to reach 2°C by the 2050s and to remain at or below this level through 2100 (Figure 2.2).

The warming trend then levels off and the global mean temperature remains nearly constant at an increase of around 2°C until the end of the century. Under the business-as-usual scenario (RCP8.5), Asian summer temperatures over land are projected to increase by 6°C by 2100 with no sign of a slowdown in the warming trend. An overview of the range of temperature increases projected by the Coupled Model Intercomparison Project Phase 5 (CMIP5) models at different time periods under both scenarios is presented in Table 2.1.

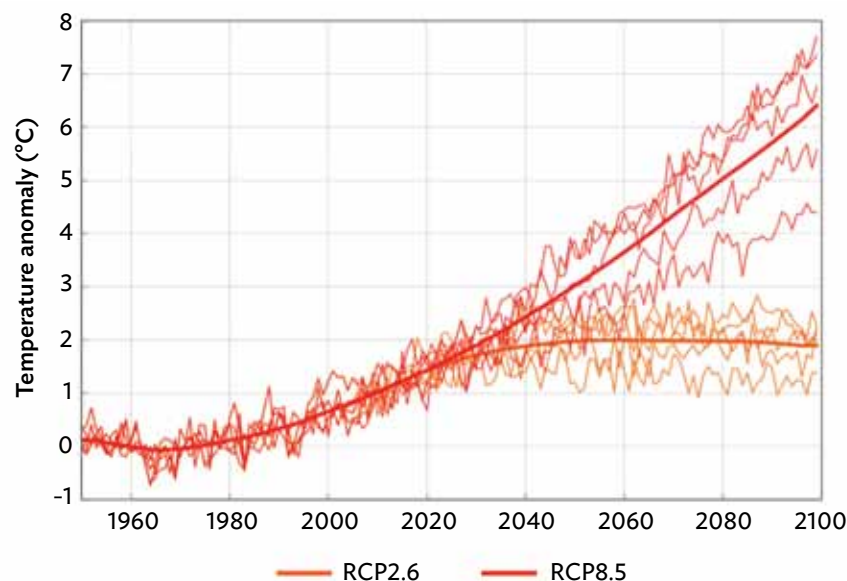
Figure 2.1: Multimodel Average Temperature Anomaly in June–August



JJA = June, July, and August; RCP = Representative Concentration Pathway.

Note: Temperature anomalies are averaged over the time period 2071–99 relative to the base period 1951–1980 and given in units of degrees Celsius (upper panels) and in units of the local historical standard deviation (lower panels). Results are shown for RCP2.6 (left) and RCP8.5 (right).

⁴ The choice of climatic baseline period will influence the estimated magnitude of temperature change. Many studies use the preindustrial period as a reference (often interpreted as 1881–1910, before which widely distributed direct measurements of temperature were not available), resulting in greater absolute change than if a late 20th century baseline is used.

Figure 2.2: Temperature Projections for the Land Area of Asia

RCP = Representative Concentration Pathway.

Note: Thick lines represent the multimodel average and thin lines individual model projections derived under the RCP2.6 and RCP8.5 scenarios for the months of June, July, and August.

Table 2.1: Projected Average Temperature Changes for the Land Area of Asia (°C)

	2030	2050	2070	2100
RCP2.6	1.6 (1.0–2.4)	1.9 (1.1–2.7)	2.0 (1.1–2.8)	1.9 (1.0–2.6)
RCP8.5	1.7 (0.7–2.4)	2.7 (1.5–3.9)	4.0 (2.5–5.5)	6.0 (3.9–7.7)

RCP = Representative Concentration Pathway.

Note: Numbers within parentheses are ranges of temperature change from different models.

Warming is stronger over higher latitudes, including central and northern Asia (Figure 2.1), where temperatures are projected to rise by 2°C–3°C under RCP2.6 and by 5°C–8°C under RCP8.5 by the end of the 21st century. Under RCP8.5, hot spots of intense local temperature increases of up to 8°C are found over the mountain ranges in the triborder region of Tajikistan, Afghanistan, and Pakistan and over the northwestern part of the PRC. Over the tropics, absolute warming is generally lower than the regional mean. This pattern of latitudinal temperature changes is evident in both scenarios.

Estimates of future temperatures in absolute terms are needed to evaluate specific risks, such as the likelihood and potential timing of exceeding important biophysical thresholds relating, for example, to important agricultural crops or disease. Additional insights can be gained by understanding temperature changes relative to historical variability, since human and environmental systems have adapted to these ranges. To assess relative change, the projected absolute temperature change is divided (normalized) by the local standard deviation (sigma). The normalized temperature change indicates how unusual

the projected temperature event would be if it occurred within the context of historical year-to-year variability in the absence of climate change. Natural variability is low in the tropics. Therefore, normalized temperature changes are particularly pronounced over tropical land areas, although absolute temperature changes may be smaller than in temperate regions (Figure 2.1).

The strongest increases in normalized temperatures are found over large parts of the PRC and Mongolia, Southeast Asia, and the southern tip of India. In these regions, projected temperatures will increase by more than six standard deviations under the RCP8.5 scenario (Figure 2.1 lower right). Such strong changes imply a shift to a new climate regime by the end of the century. To provide perspective, a temperature shift of six standard deviations implies that the coldest summer months at the end of the 21st century are projected to be warmer than the warmest summer months during the base period in 1951–1980.

Changes in Heat Extremes

In this study, heat extremes are defined by the exceedance of temperature thresholds calculated on the basis of local historical year-to-year variability, since human societies and ecosystems are adapted to these conditions. The most pronounced heat extremes will occur over regions where the absolute temperature increase is large relative to local natural variability. In the tropics, where natural variability is low, a relatively small absolute temperature increase might lead to severe impacts. For example, coral reefs in the tropics are very sensitive to temperature changes and will already face almost complete extinction at 2°C warming (Frieler et al. 2013). By contrast, over northern Asia, the same amount of absolute warming may have relatively less impact due to the much wider natural temperature variability range.

In some cases, heat extremes must be defined with respect to absolute temperature thresholds. Many of these thresholds reflect biophysical processes. For

example, Sherwood and Huber (2010) observe that under global mean warming of 7°C, small regions develop where the *wet bulb* temperature might exceed 35°C for extended periods, making dissipation of metabolic heat impossible and resulting in hyperthermia in humans and other mammals.⁵ Under these conditions, survival under exposed conditions is not possible. While acknowledging the importance of absolute temperature thresholds, this study focuses on relative thresholds to allow for more general discussions on impacts.

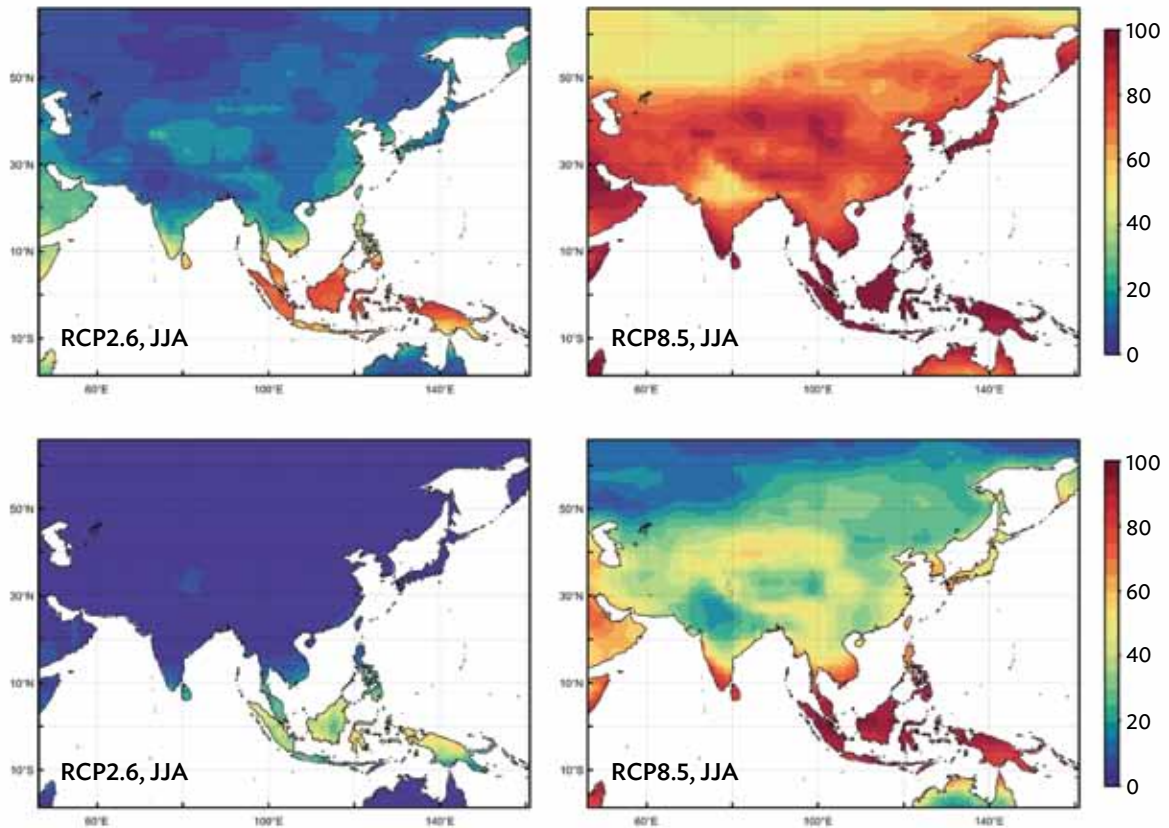
In a stationary climate with no long-term warming, a summer with mean temperatures equal to or greater than three standard deviations above the mean (3-sigma event) would be considered very rare, in general occurring less frequently than once per century.⁶ A 5-sigma event would then be significantly less frequent, implying that such an event is essentially unprecedented under today's climate conditions. Model projections show that under the business-as-usual scenario, summers that are 3-sigma events relative to historical climate might be the new normal by the end of this century over nearly all land regions (Figure 2.3). Restated, monthly mean summer temperatures are projected to exceed the 3-sigma threshold every other year on average. Moreover, summer temperatures exceeding the 5-sigma threshold might become common over most continental land areas with 20%–60% of summer months exceeding 5-sigma over the time period 2071–2099, depending on the warming scenario.

Southeast Asia is projected to be the region most affected by heat extremes (Figure 2.3). In this region, unprecedented high summer temperatures are expected to return every year if warming continues to rise as projected under RCP8.5. Limiting global warming to 2°C would reduce the occurrence of heat extremes to a significant extent. Under RCP2.6, models project the share of 3-sigma events to be around 70% over Southeast Asia and 0%–40% over continental Asia toward the end of the 21st century.

⁵ The wet bulb temperature is the temperature that can be maintained through evaporative cooling, such as via perspiration, and depends on both measured (“dry bulb”) air temperature and relative humidity.

⁶ In a stationary climate, summer temperatures at a given location are distributed approximately symmetrically around the mean summer temperature. In most regions, most of the distribution is well described by the Gaussian (normal) distribution. However, the frequency of extreme or “tail” events (e.g., 3 sigma or greater) generally will not be accurately described by the Gaussian distribution (Sardeshmukh, Compo, and Penland 2015) and are more appropriately modeled using extreme value distributions.

Figure 2.3: Projected Frequency of Heat Extremes



JJA = June, July, and August; RCP = Representative Concentration Pathway.

Note: Colors indicate the multimodel average of the percentage of boreal summer months in the time period 2071–2099 with temperatures greater than three standard deviations (3-sigma, top panels) and five standard deviations (5-sigma, bottom panels) for the RCP2.6 (left) and RCP8.5 (right) scenarios. Standard deviation is calculated for the baseline period (1951–1980).

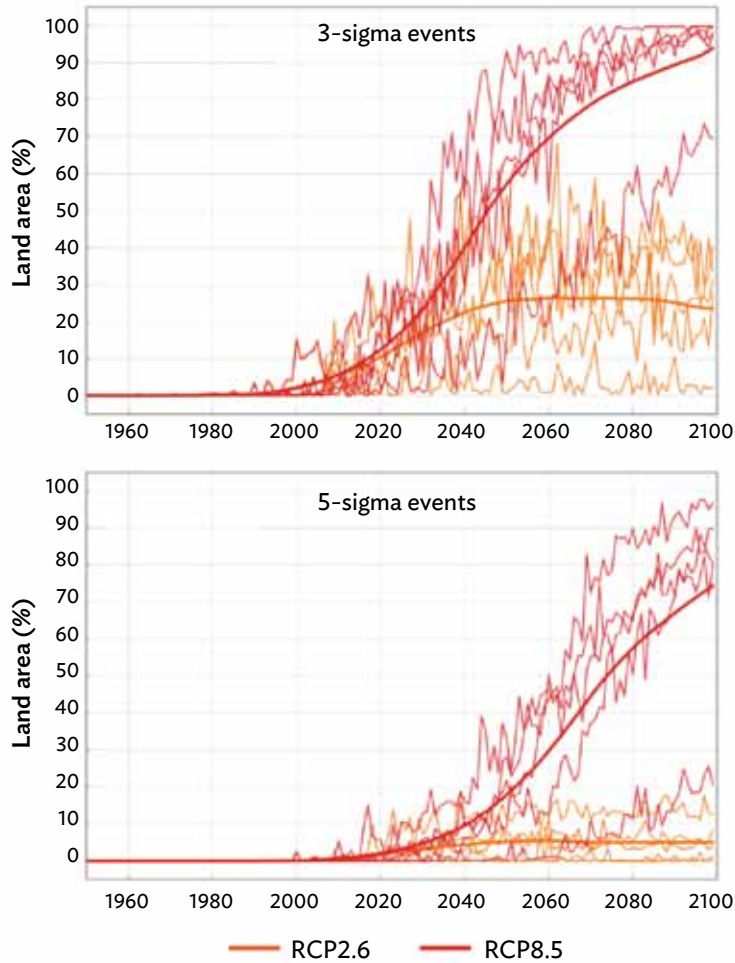
However, 5-sigma events can be almost entirely avoided under the Paris-consensus scenario over most Asian land regions, except for Southeast Asia, where such extreme summers are projected to occur every 2–5 years.

The percentage of land area experiencing heat extremes increases significantly with global warming (Figure 2.4). Assuming the multimodel mean projection under the Paris-consensus scenario, the percentage of Asian land experiencing 3-sigma summers is limited to less than 30%. For that case, temperatures greater than 5-sigma are projected to cover around 5% of all Asian land (particularly in Southeast Asia) in the time period 2071–2099. However, under business as usual, almost all of Asia's

land area is projected to experience 3-sigma summers nearly continuously by the year 2100. Average summer temperatures over 70% of the land area are projected to be larger than 5-sigma by the end of the century.

The risk of experiencing heat extremes at different levels of global warming is summarized from the time series plots in Figure 2.4 (see also Table 2.2). In a 6°C warmer world, most of Asia's land area is expected to experience unusual or unprecedented heat extremes. Limiting global warming to 2°C above preindustrial levels significantly reduces the percentage of land area at risk of heat extremes. More importantly, limiting global warming to 1.5°C further reduces the risk of severe heat extremes by a factor of two.

Figure 2.4: Projected Percentage of Land Area Affected by Heat Extremes



RCP = Representative Concentration Pathway.

Note: Multimodel average (thick line) and individual model simulations (thin lines) of the percentage of Asian land area with monthly mean temperatures during the summer (June–August) warmer than 3-sigma (top panel) and 5-sigma (bottom panel) for the RCP2.6 and RCP8.5 scenarios.

Table 2.2: Percentage of Land Area at Risk of Heat Extremes (%)

	Around 1.5°C (2020)	Around 2°C (2030)	Around 6°C (2090)
Unusual heat extreme (3-sigma)	14	27	91
Unprecedented heat extreme (5-sigma)	3	6	70

2.2 Changes in Precipitation and Heavy Rainfall Events

Changes in rainfall can impose great challenges on both human society and natural ecosystems. Whereas intense rainfall can lead to severe flooding, consecutive months of low rainfall can lead to droughts, both resulting in agricultural losses. In southern Asia, rainfall is primarily driven by the monsoon. The complex processes involved within and between the Indian and Australian monsoon systems make it particularly difficult to project rainfall

changes over this region. Climate models project a general upward trend in annual mean precipitation over most Asian land areas toward the end of the 21st century. However, the magnitude of change is much larger under the business-as-usual scenario (RCP8.5) as compared to the Paris-consensus scenario (RCP2.6). India is a special case, where rainfall is projected to increase during the rainy season while decreasing in the dry season.

Projected changes in mean climate states (e.g., global mean annual precipitation) are relatively well documented in the climate research literature. It is far more difficult to detect and to project changes in extreme events, i.e., in the upper tails of the rainfall distribution. This is because tail events, by definition, are observed less frequently and are poorly simulated by general circulation models (GCMs) since they often result from complex and dynamic processes at short lengths and timescales. Projected changes in extreme precipitation events are therefore more uncertain than changes in annual and seasonal accumulation. However, both observations and state-of-the-art climate models show a pronounced increase in the frequency and intensity of heavy rainfall events, particularly over Southeast Asia. This region might therefore anticipate more severe flooding in the future as the global temperature continues to rise.

One of the primary impacts of climate change is alterations in the hydrological cycle (Trenberth 2011). Rising temperatures will lead to higher evaporation rates, as the water-holding capacity of the atmosphere increases by around 7% per degree of warming, fueling comparable increases in the intensity of heavy daily rainfall events (Pall, Allen, and Stone 2007; Westra et al. 2014) although not in average rainfall (Allen and Ingram 2002). Water vapor is also a potent greenhouse gas, creating a positive feedback mechanism. Increased evaporation also results in more surface drying, particularly when rainfall is concentrated in fewer, more intense events. This leads to projected changes in rainfall patterns that have been broadly generalized as “the wet gets wetter and the dry gets drier.”

Climate change also affects atmospheric circulation patterns in ways which will disrupt this simplified conceptualization of rainfall changes (Lehmann and Coumou 2015). Rainfall changes in southern Asia are particularly difficult to assess because precipitation is strongly determined by the monsoon system. Climate

models currently have limited success in reproducing the monsoon mechanisms accurately, and, although the latest generation of climate models shows improved skill in capturing observed monsoon circulation, significant uncertainties remain (IPCC 2013).

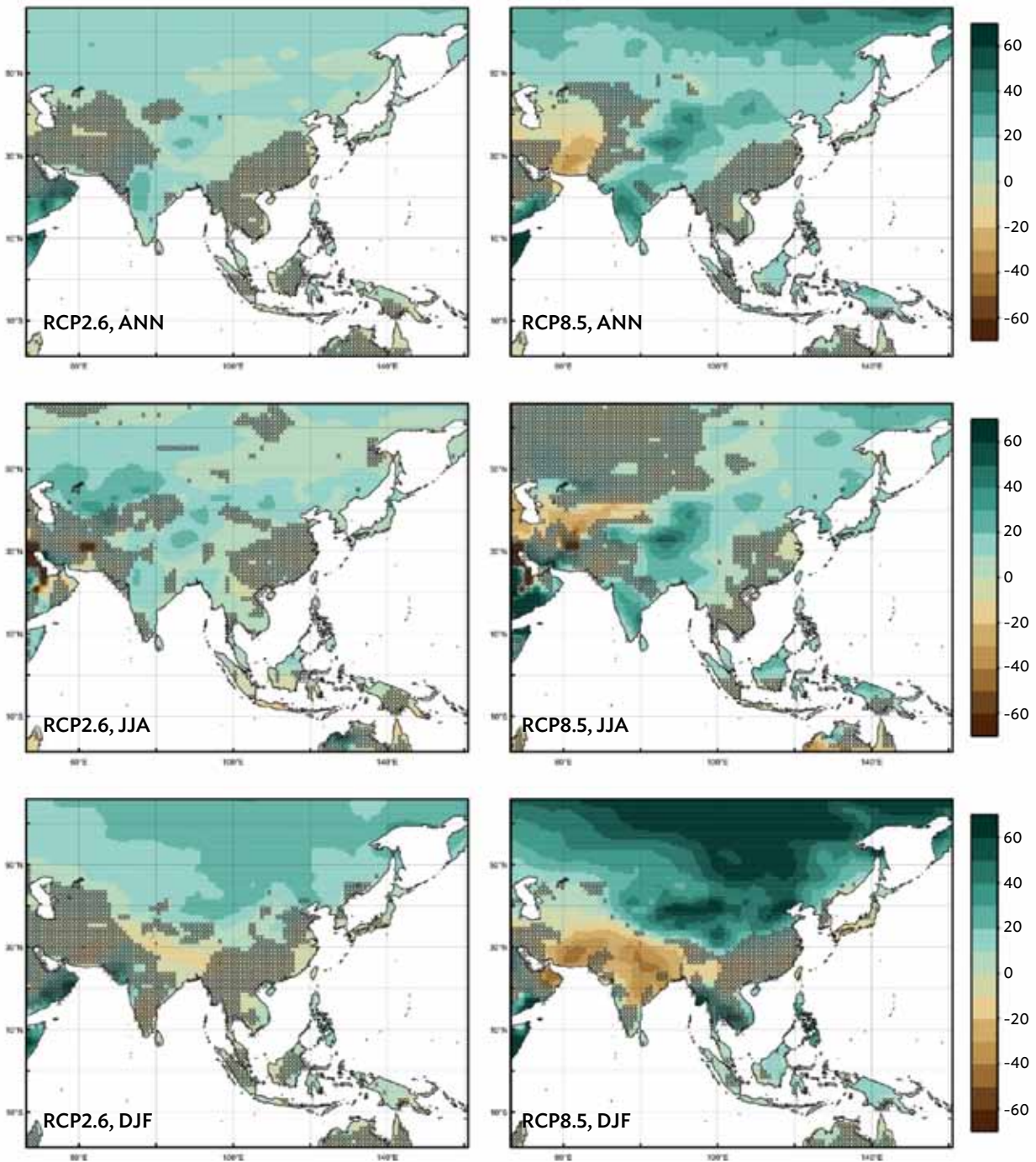
The monsoon system is a critical factor for the water supply over large parts of Asia. Fully 80% of India’s total annual rainfall occurs during the summer monsoon season. A study by Levermann et al. (2009) suggests that the Asian monsoon system could abruptly shift from a state with strong rainfall to a weak precipitation state. Since agricultural productivity over the PRC and India is closely linked to monsoon rainfall, such a shift would have profound impacts on regional food security (Krishna Kumar et al. 2004; Tao et al. 2004).

Projected Changes in Precipitation

The same set of Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) model simulations (Warszawski et al. 2014) used in the analysis of temperature changes is used to assess changes in precipitation. The simulations produced by the CMIP5 climate models were bias-corrected so that the observed historical mean and variation in precipitation are reproduced (Hempel et al. 2013). Most Asian countries experience a rainy season and a dry season. For this study, the rainy (monsoon) season is defined as the months June, July, and August (JJA) and the dry season as the months December, January, and February (DJF). This simplified assumption is applicable to regions north of the equator, encompassing the majority of countries included in this analysis, although the seasonality of rainfall is reversed south of the equator, including Indonesia.

Under the business-as-usual scenario, annual mean precipitation is projected to increase in the late 21st century by up to 50% over most land areas (Figure 2.5). By contrast, in a region including Pakistan and Afghanistan, annual mean precipitation is projected to decline by 20%–50% over this period. Changes in annual mean precipitation under the Paris-consensus scenario are smaller in magnitude with projected increases less than 30%. Although the general trend is toward increasing annual mean precipitation, there are many regions where uncertainty in projected precipitation change is large. Models show disagreement on the direction of precipitation change over many regions, including large

Figure 2.5: Projected Change in Precipitation



ANN = Annual; DJF = December, January, and February; JJA = June, July, and August; RCP = Representative Concentration Pathway.

Note: Multimodel average of the percentage change in annual (top panels), wet season (JJA, middle panels), and dry season (DJF, bottom panels) precipitation for the RCP2.6 (left) and RCP8.5 (right) scenarios over Asian land by 2071–2099 relative to 1951–1980. Hashed areas indicate regions where models disagree on the direction of change.

parts of western and eastern Asia and over nearly all of Southeast Asia. This is evident in both scenarios, although *relative* uncertainty is larger under the RCP2.6 scenario for which projected rainfall changes are less dramatic when compared to natural interannual variability.

Projected precipitation changes during the wet season follow a pattern similar to annual mean precipitation, although there are larger areas over which models disagree. Over South Asia, particularly over India during the dry season, rainfall is expected to decline toward the end of the 21st century under RCP8.5 in contrast to the projected increase in wet season. Hence, the Indian monsoon is projected to increase in intensity and variability under unabated climate change. The finding is in agreement with previous studies which suggest that under global warming the seasonal precipitation range between the wet and dry seasons is enhanced in the tropics (Chou, Tu, and Tan 2007; Menon et al. 2013).

An exception to the “dry gets drier” generalization is seen over Central Asia where arid regions are expected to see more rainfall independent of the season, but in particular during the dry season.

Precipitation over Southeast Asia is particularly difficult to project because in this region rainfall is influenced by the interplay between both the Indian and Australian monsoon (Hung, Liu, and Yanai 2004). Model agreement is generally low over this region independent of the scenario and season (Figure 2.5).

Changes in Extreme Precipitation

Trends toward more intense heavy rainfall events have been observed globally (Alexander et al. 2006; Sillmann et al. 2013a; Westra, Alexander, and Zwiers 2013). The number of record-breaking rainfall events has significantly increased over the last decades with the strongest increases globally found over Southeast Asia. Lehmann, Coumou, and Frieler (2015) show that over the period 1981–2010, the number of daily rainfall events setting new local records nearly doubled over this region, which are implicitly associated with long-term warming. This is consistent with CMIP5 model projections which show significant increases in the frequency and intensity of heavy rainfall events over Southeast Asia as well as over large parts of the Asian mainland (Sillmann et al. 2013a).

It has been shown that the increase in extreme rainfall intensity is generally consistent with the increased water-holding capacity in a warmer atmosphere (Pall, Allen, and Stone 2007) which in turn links these changes to anthropogenic GHG emissions (Zhang et al. 2007; Fischer and Knutti 2015). Upward trends in the frequency and intensity of heavy rainfall events are therefore expected to continue over the coming century (Sillmann et al. 2013b). Fischer, Beyerle, and Knutti (2013) show that uncertainty in near-term projections of precipitation extremes can be reduced by averaging over larger spatial scales. They report robust upward trends in projected heavy precipitation intensities over essentially all of Asia, providing valuable information for stakeholders and decision makers involved in risk management.

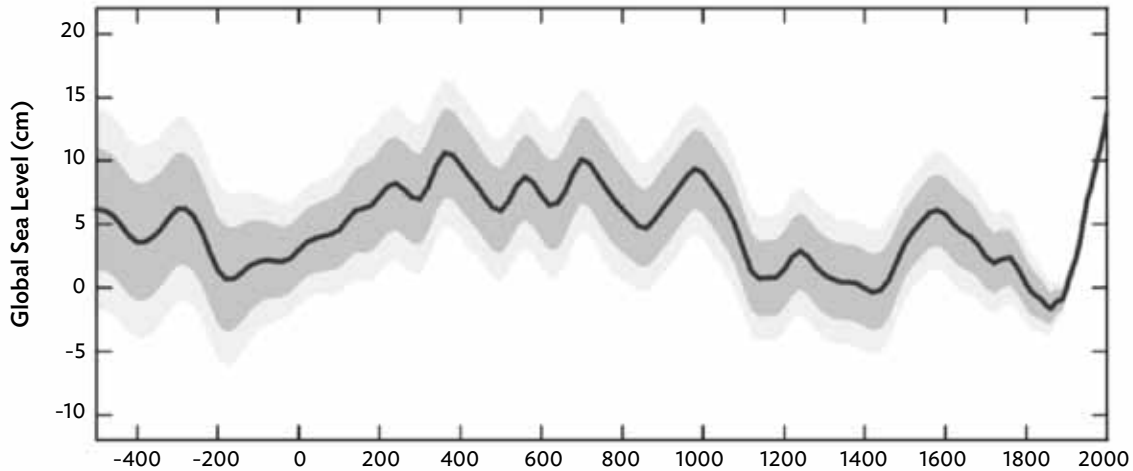
The societal consequences of changing patterns of rainfall accumulation and intensity cannot be interpreted directly from projections alone, since vulnerability in specific contexts depends not only on the frequency and intensity of rainfall events but on other nonclimatic parameters including topography and soil properties as well as on human interventions including physical flood protection measures, warning, and evacuation procedures (Hijjoka et al. 2014).

2.3 Sea-Level Rise

Asia’s vulnerability to sea-level rise (SLR) is particularly strong given that a large share of Asia’s population and urban centers are located in low-lying coastlines.

The increase in global mean temperature has caused a global mean SLR of about 0.19 meters (m) during the last century (IPCC 2013). This was the largest sea-level increase of the past 25 centuries and is strongly correlated with the anthropogenically induced global temperature increase (Kopp et al. 2016) (Figure 2.6). The primary mechanisms driving global mean SLR in the postindustrial period include thermal expansion of ocean water, the melting of glaciers and continental ice sheets, and ice sheet dynamics (IPCC 2013). Many other factors act to determine the rate of sea-level rise in specific locations, including isostatic rebound from previous glacial episodes, overextraction of groundwater in coastal aquifers, and reduction in the supply of sediments to river deltas due to upstream dam construction.

Figure 2.6: Reconstructed Sea-Level Rise over the Last 2,500 Years



Future SLR will depend on the additional warming that will be induced by GHG emissions if carbon emissions are not reduced drastically. However, even if dramatic reductions in GHG emissions are achieved, SLR will continue to increase on the basis of historical warming, since the earth–ocean system requires centuries to millennia to reach equilibrium (Figure 2.7).

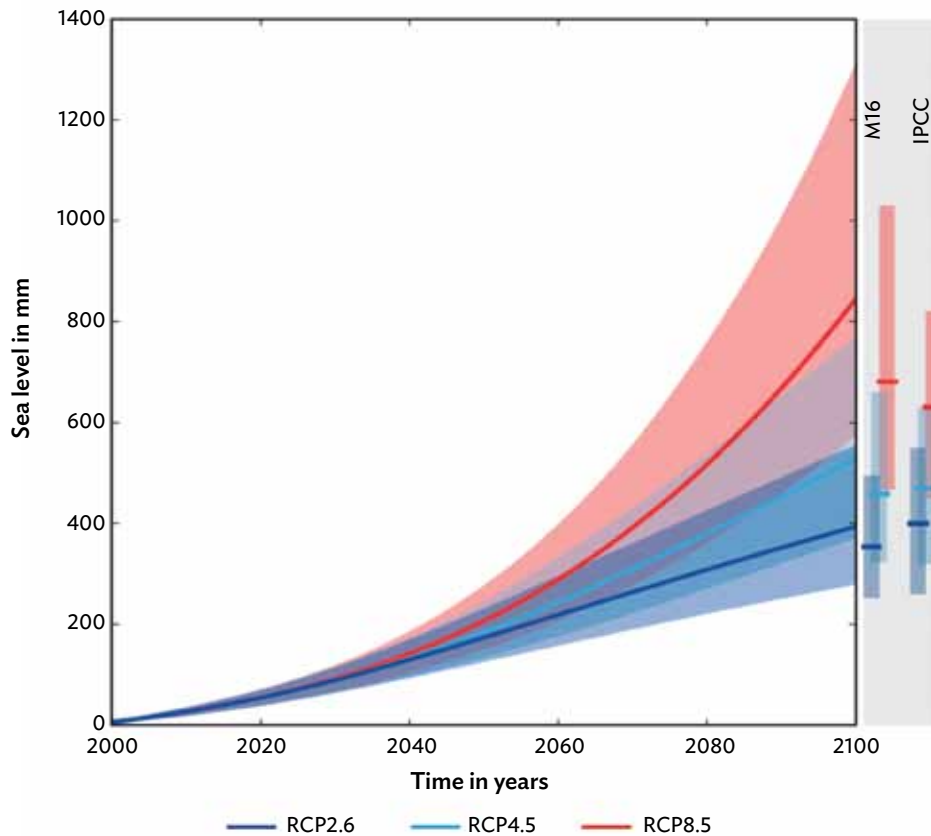
In the last century, the observed global SLR has been caused mainly by the thermal expansion of the ocean (about 40%) and the melting of mountain glaciers (about 35%) (Gregory et al. 2013). Since the early 1990s, the large ice sheets on Greenland and Antarctica have lost ice at an increasing rate (Figure 2.8). Since Greenland contains enough ice to raise the sea level globally by 7 m and Antarctica by 55–60 m (Levermann et al. 2013), it is crucial to understand how much ice will be lost from these ice sheets under future warming.

The thermal expansion of the ocean increases with the warming at the surface and becomes stronger over time because the heat is gradually mixed into the deep ocean and an increasing depth of ocean expands. This process is reasonably well understood, but there is uncertainty in the details of the pattern and magnitude of the expansion due to uncertainty in projected future ocean circulation and mixing processes (Domingues et al. 2008). Significant progress has been made in recent years in determining the melting of mountain glaciers under different warming

scenarios (Marzeion et al. 2014). The scientific community does not anticipate new revelations that would dramatically alter the projections.

The Greenland ice sheet has been contributing to SLR during the past 2 decades. About half the mass loss from Greenland occurs through surface melt and half through the discharge of icebergs. Iceberg calving has increased in recent years, primarily through three outlet glaciers in the southern half of the Greenland ice sheet. While a rapid contribution to sea level is possible through acceleration of these outlet glaciers (Howat et al. 2010), the total contribution over the next century is assumed to be limited to about 0.1 m. Whether surface melt will increase and whether an accelerated ice loss is to be expected from this process are unknown. The surface melt can be projected into the future with some uncertainty (Fettweis et al. 2013), but questions remain as to whether there exists a self-amplifying mechanism. Such a mechanism has been proposed because the physical properties of ice and snow change with surface melting. Snow and ice that have been partially melted absorb more solar radiation than freshly formed and cold snow and ice. Such energy absorption can lead to more melting. If this self-amplifying effect is found to be much stronger than presently assumed in the models, the contribution from the Greenland ice sheet could become significantly larger than currently projected (Box et al. 2012).

Figure 2.7: Projected Total Anthropogenic Sea-Level Rise for the 21st Century



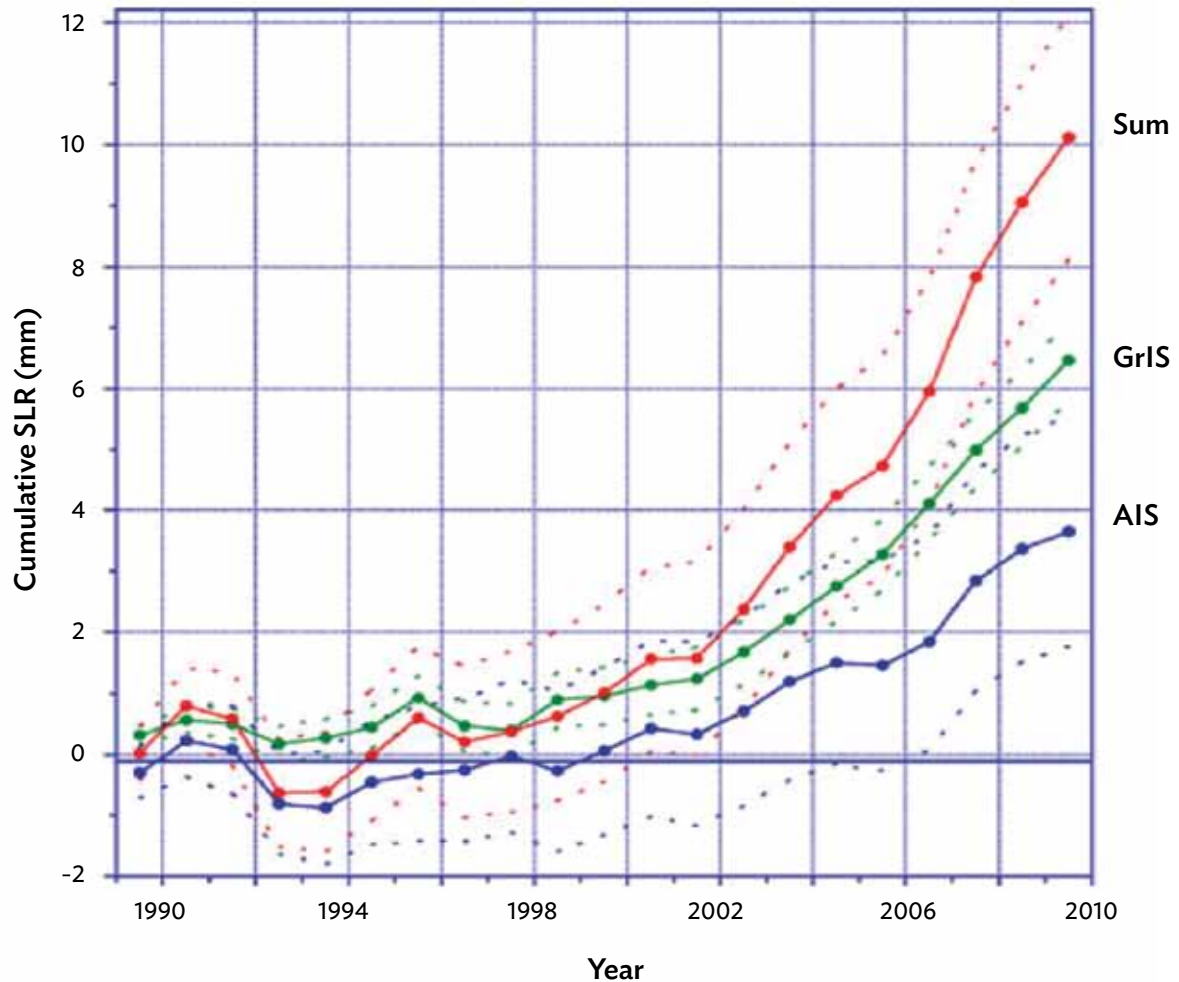
IPCC = Intergovernmental Panel on Climate Change, M16 = Mengel et al. (2016), mm = millimeter, RCP = Representative Concentration Pathway. Note: Median (thick line) and 5th–95th percentile uncertainty range (shading) of projected total anthropogenic sea-level rise for three warming scenarios used by the IPCC Fifth Assessment Report (AR5). Bars at the right show the 5th–95th percentile range of the study by Mengel et al. (2016), and the IPCC AR5 likely ranges intersected by the median for 2081–2100. All are relative to the 1986–2005 mean. The scenario with climate protection (the corresponding sea-level rise is given in blue) keeps the global mean temperature increase below 2°C of warming, while temperatures rise by about 5°C without climate mitigation (corresponding sea-level rise in red). Strong climate change mitigation can reduce the 21st century sea-level rise by a factor of two.

Sources: J. A. Church et al. 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. Cambridge, UK, and New York, NY: Cambridge University Press; M. Mengel et al. 2016. Future Sea Level Rise Constrained by Observations and Long-Term Commitment. *Proceedings of the National Academy of Sciences*. 113. pp. 2597–2602.

Using past observations and knowledge about the eventual total ice loss at different temperature levels (the so-called sea-level commitment), Mengel et al. (2016) projected the sea-level contributions from various sources for the 21st century (Table 2.3). These projections are consistent with those derived using other methodologies (Jevrejeva, Moore, and Grinsted 2010; Kopp et al. 2016; Rahmstorf 2006; Slangen et al. 2014; Vermeer and Rahmstorf 2009) and the IPCC projections (Church et al. 2013) but suggest a slightly higher upper limit of 21st century SLR.

The upper limit arises primarily due to uncertainty in the contribution of the Antarctic ice sheet. While Antarctica is very cold and is not near the threshold for strong surface melting of the ice sheet even under strong future warming scenarios, ice loss occurs due to interaction with the surrounding ocean via iceberg calving. The IPCC (2013) estimated the contribution through this process to be between 0.01 m and 0.16 m within the 21st century. Levermann et al. (2014) found a larger uncertainty and estimated that the sea-level contribution could be as high

Figure 2.8: Sea-Level Contribution of the Large Ice Sheets



SLR = sea-level rise.

Note: Sea-level contribution of the large ice sheets on Greenland (GrIS) and Antarctica (AIS) over the satellite period. During the last 2 decades, the ice sheets have started to contribute to global SLR at an accelerating rate.

Source: M. R. van den Broeke et al. 2011. Ice Sheets and Sea Level: Thinking Outside the Box. *Surveys in Geophysics*. 32(4-5), pp. 495-505.

as 0.4 m if only known physical processes are at play. The projections by Mengel et al. (2016) are consistent with this larger uncertainty range (Table 2.3).

Deconto and Pollard (2016) introduced two new processes into their physical model of the Antarctic ice sheet and projected that its contribution to SLR could be as large as 1 m within the 21st century. This new study awaits validation

by subsequent research, but it shows that there is still some uncertainty with respect to the Antarctic contribution to future SLR which needs to be constrained. The Antarctic contribution constitutes the largest uncertainty with respect to future global mean sea-level projections.

Due to the complexity of these physical processes, it is difficult to project the temporal evolution of future sea

Table 2.3: Projected Contribution to Future Sea-Level Rise for 2100 Relative to the Reference Period 1986–2005 (mm)

Contribution	RCP2.6	RCP4.5	RCP8.5
Thermal expansion	149.0 (66.2–228.0)	194.0 (85.8–303.0)	291.0 (120.0–454.0)
Mountain glaciers	79.0 (62.4–103.0)	93.2 (72.5–122.0)	109.0 (84.8–147.0)
Greenland SID	47.4 (35.1–87.2)	55.7 (41.5–109.0)	74.1 (50.8–147.0)
Greenland SMB	69.7 (40.1–116.0)	117.0 (69.3–214.0)	266.0 (152.0–518.0)
Antarctica SID	64.4 (40.4–91.0)	85.4 (55.9–124.0)	128.0 (88.8–189.0)
Antarctica SMB	-16.0 (-26.3 to -7.9)	-20.3 (-33.7 to -9.96)	-28.6 (-48.3 to -13.8)
Total	393.8 (279.9–555.5)	529.0 (370.8–772.7)	845.5 (574.1–1,312.0)

RCP = Representative Concentration Pathway, SID = solid ice discharge, SMB = surface mass balance.

Note: The first number of each cell stands for the median estimated contribution. The first number within the brackets stands for the 5th percentile and the second number within the brackets stands for the 95th percentile.

Source: M. Mengel et al. 2016. Future Sea Level Rise Constrained by Observations and Long-Term Commitment. *Proceedings of the National Academy of Sciences*. 113. pp. 2597–2602.

level, and considerable research efforts are reflected in the estimates presented in Table 2.3. Although counterintuitive, it is methodologically easier to develop estimates of SLR associated with different warming levels in the very long term. The reason is that it is possible to estimate which ice masses can be sustained at different temperature levels and which cannot (Winkelmann et al. 2015). Consistent with past climate observations, it has been estimated that for every degree of global warming, the sea level will eventually rise by about 2.3 m (Levermann et al. 2013). This very long time perspective is relevant to humankind's cultural heritage, among other concerns. It was estimated that under unmitigated future warming, a large number of countries will lose more than 10% of their land area (Marzeion and Levermann 2014). As warming progresses to 3°C, an increasing number of UNESCO cultural heritage sites will be threatened by SLR.

Regional Sea-Level Rise in Asia and the Pacific

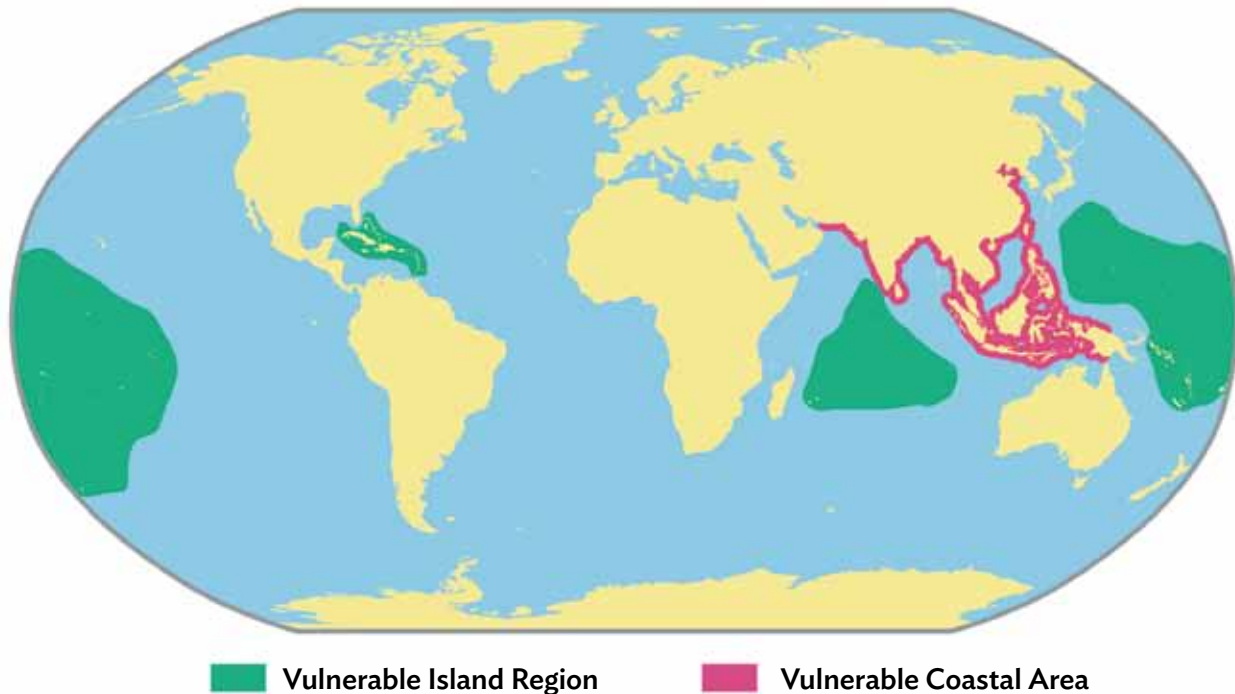
Regional sea-level changes can differ significantly from the global mean due to changes in ocean circulation (Levermann et al. 2005) and gravitational effects from the ice loss (Mitrovica et al. 2001). The gravitational effects are generally not larger than 25% of the global mean SLR. Sea-level changes resulting from ocean circulation changes can be of the order of 1 m, depending on the strength of the

ocean current that is changing. Other factors such as local relative land surface depression due to isostatic rebound from past glaciation can contribute to local relative rates of SLR that exceed the effect of the global mean. These effects, however, will play a minor role in most of Asia since it was not glaciated in the past, but slight remote effects might be relevant in some regions.

Other location-specific factors that will influence local SLR include land subsidence from the overextraction of groundwater. In deltaic areas, the compression of sediments and erosion of coastal land by wave action can increase relative SLR. These processes are exacerbated by both SLR itself and the reduced delivery of sediments to deltas where dams are constructed upstream.

While the North Atlantic Current has shown a weakening during the last century (Rahmstorf et al. 2015) and is projected to decline further under future warming (Gregory et al. 2005), this has not been observed or projected for the equivalent northern boundary current along the Asian east coast. Whether clear trends can be identified in the ocean current in the Indian Ocean or at the Indonesian throughflow will require future research, but currently there is no indication that a sudden change in any large-scale Asian ocean current is anticipated. Consequently,

Figure 2.9: Coastal Regions Most Vulnerable to a Climate Change-Related Sea-Level Rise (Asia and the Pacific)



Source: Based on R. Nicholls et al. 2010. Economics of Coastal Zone Adaptation to Climate Change. World Bank Discussion Papers No. 10. Washington, DC: World Bank.

regional sea-level deviations from the global mean are projected to be significantly below 0.5 m due to ocean circulation changes.

The gravitational effect of ice loss increases with distance from the ice mass that has been reduced. As a consequence, the SLR in the northern hemisphere from a contribution from Greenland is smaller than the global mean, while Antarctic ice loss results in a stronger SLR in the north. The tropics and most of the small island states are impacted significantly by mass loss from both ice sheets. A specific analysis for the Asian region is desirable but has not been conducted to date.

Assessments of impacts from SLR are either based on case studies or are aggregated on much larger scales. Although Hunt and Watkiss (2011) reported that climate risks most frequently addressed in existing studies are associated with SLR, health, and water resources, only a small

number of cities, mostly in countries of the Organisation for Economic Co-operation and Development (OECD), have derived quantitative estimates of the costs of climate change risks under alternative scenarios.

Coastal regions of Asia and the Pacific are among those most vulnerable to climate change-related SLR (Figure 2.9). Flood exposure is apparently increasing in coastal cities due to growing populations and assets, SLR, and subsidence (Hallegatte et al. 2013). Studying the 136 largest coastal cities, the authors estimate that the average global flood losses in 2005 were approximately \$6 billion per year and will increase to \$52 billion by 2050. Of the top 20 cities with the largest increase of annual losses between 2005 and 2050, 13 are located in Asia: Guangzhou (PRC), Mumbai (India), Kolkata (India), Shenzhen (PRC), Tianjin (PRC), Ho Chi Minh City (Viet Nam), Jakarta (Indonesia), Chennai–Madras (India), Surat (India), Zhanjiang (PRC), Bangkok (Thailand), Xiamen (PRC), and Nagoya (Japan).

This illustrates the strong exposure of Asian cities. Brecht et al. (2012) showed that 19 of the 25 cities most exposed to a 1 m SLR are located in the Asia and Pacific region, 7 of which in the Philippines alone.

Assuming no adaptation and a relative SLR of approximately 0.45 m at the end of the century, Indonesia is projected to be most affected by coastal flooding, with nearly 5.9 million people affected annually in 2100 (McLeod et al. 2010). Moreover, according to Hinkel and Klein (2014), 0.2%–4.6% of the global population is expected to be flooded annually in 2100 under 25–123 centimeters (cm) of global mean SLR and without adaptation, with expected annual losses of 0.3%–9.3% of global GDP.

Neumann et al. (2015) showed that the number of people exposed to flooding from 1-in-100-year storm surge events is the highest in Asia—that is, in the PRC, India, Bangladesh, and Indonesia. As Hanson et al. (2011) stated, 65% of the global exposed population living beneath the 100-year water level is attributed to Asian port cities. Bigano et al. (2008) estimated a GDP loss of 0.1% in Southeast Asia for an SLR of 25 cm by 2050. Greenpeace (2008) estimated that in India, Bangladesh, and Pakistan approximately 130 million people reside in low-elevation coastal zones and are at risk of being displaced by the end of the 21st century under worst-case scenarios.

The scientific literature assessing local impacts of SLR in Asia is very limited and only a few examples are investigated in detail. Le et al. (2007) found that SLR will enhance flooding in the Mekong River Delta in Viet Nam and that flooding may worsen in the long term as a result of estuarine siltation resulting from the construction of dams. Marfai and King (2008) outlined that the Semarang coastal area in Indonesia is subject to coastal hazards due to tidal inundation and land subsidence and that the impact of the inundation is predicted to be even more severe in the scenario with SLR.

2.4 Tropical Cyclones

Tropical cyclones pose major risks to societies worldwide. According to Munich Re's NatcatService Database, accumulated economic losses (in nominal value) between 1980 and 2014 exceeded \$750 billion globally, equivalent

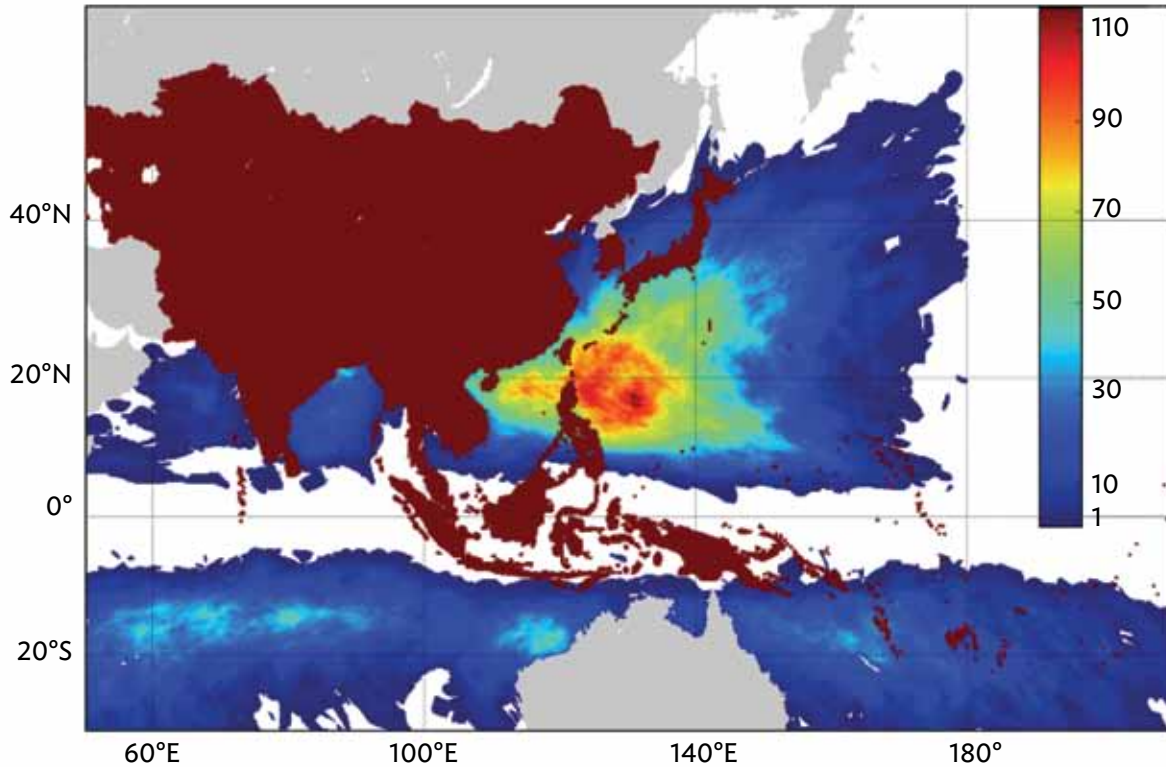
to \$30 billion per year. Over the same period, an estimated 400,000 people were killed as a consequence of tropical cyclones making landfall in populated areas.

Tropical cyclone damage from climate change tends to be concentrated in North America, East Asia, and the Caribbean–Central American region. The Western Pacific Ocean (WPO) is the most active tropical cyclone region on earth (Ho et al. 2004). Tropical cyclone activity in the Southern Pacific Ocean, North Indian Ocean, and to some degree in the Southern Indian Ocean must be considered when evaluating impacts on countries located in the Asia and Pacific region (Figure 2.10). According to Munich Re, tropical cyclone losses in the countries of the region (\$220 billion) are equal to 30% of total global losses between 1980 and 2014. The number of fatalities over the same period amounts to more than 374,000, representing 93% of global mortality, indicating the high vulnerability of Asia and the Pacific to the tropical cyclone hazard. Fatalities tend to be associated with the most extreme events. Two events—tropical cyclone Nargis in Myanmar in 2008 and the Bangladesh cyclone in 1991—alone caused almost 280,000 deaths, representing 75% of all fatalities in the Asia and Pacific region over the entire period.

Minimizing future tropical cyclone impacts by reducing vulnerabilities and enhancing the adaptation potential should be the goal of regional and local authorities, particularly as current studies find an increase in absolute tropical cyclone losses across the globe (Narita, Tol, and Anthoff 2008). Socioeconomic and climatic changes are each expected to result in a doubling of future losses by 2100 (Mendelsohn et al. 2012). Large countries such as the PRC are projected to be most affected in absolute terms while small island states will bear the highest relative burden (Narita, Tol, and Anthoff 2008). However, uncertainties are multifold and efforts to reduce them must be enhanced. A recent meta-analysis of studies analyzing the effects of climate change reported an increase in mean losses of 28% for 2.5°C of global warming for the WPO, but with 95% uncertainty ranging from –49% to 166% (Ranson et al. 2014).

Ranson et al. (2014) first focused on current research on a more disaggregated subregional or country level. They then examined what is known about the future risk posed by tropical cyclones for the Asia and Pacific region. Risk is defined as a function of the tropical cyclone hazard, the

Figure 2.10: Tropical Cyclones Frequency in Asia and the Pacific
(number of events between 1980 and 2014)



Note: Color coding over the oceans shows the observed number of tropical cyclones between 1980 and 2014 for all events with a minimum wind speed of 34 knots. Note the pronounced tropical cyclone activity in the Western Pacific but also tropical cyclones in the North and Southern Indian and Southern Pacific Ocean affect countries in Asia and the Pacific.

exposure of societies at risk, and their specific vulnerability. Each of the three risk components have been projected or are actively under research. However, research is required to understand the combined influences of projected tropical cyclone frequency and intensity, impacts on societies reflecting specific socioeconomic development pathways, and country-specific vulnerability and resulting losses (Noy 2016). In the absence of such integrative research, the variation in impacts caused by different global warming scenarios cannot presently be quantified. Such integrative research is required to determine the benefits of climate mitigation versus adaptation at the level of individual countries.

Tropical Cyclones and Societies: the Current Situation

Hazards associated with tropical cyclones include extremely strong winds, torrential rain, and severe storm surges. Depending on the location of impact, the societal development standard, and the predisaster safety and evacuation measures, tropical cyclones cause injuries and fatalities and they destroy or damage capital stock, infrastructure, and land. Figure 2.10 shows the spatial (grid) distribution of the historic tropical cyclone hazard for Asia and the Pacific between 1980 and 2014 standardized to average event frequency per century. The observed tropical cyclone activity exhibits a complex internal variability and

it is difficult to isolate the influence of anthropogenic climate change (Colbert, Soden, and Kirtman 2015; Crompton, Pielke, and McAneney 2011; Estrada, Botzen, and Tol 2015; Knutson et al. 2010), particularly as the period of reliable satellite-based observations (Knapp et al. 2010) extends only to the early 1980s, which coincides with the periodicity of multidecadal climate variability, e.g., the Pacific Decadal Oscillation.

The world has recently experienced a period of increasing tropical cyclone destructiveness that appears proportional to the observed increase in sea surface temperature (Elsner, Kossin, and Jagger 2008; Emanuel 2005). The change in destructive power is associated with an increase in the strongest tropical cyclones, although the frequency of weak tropical cyclones has decreased (Holland and Bruyère 2014) with an overall reduction of global tropical cyclone numbers (Kang and Elsner 2015).⁷ At the basin level, upward trends in lifetime maximum intensity are significant in all basins except for the WPO (Kossin, Olander, and Knapp 2013). For the WPO, it has been shown that the overall frequency decrease is accompanied by an increasing number of very strong tropical cyclones (Kang and Elsner 2012), a finding confirmed by dynamically rerunning historical cyclones with tropical cyclone models (Wu and Zhao 2012). Similar trends have also been identified recently for the North Indian Ocean (Singh 2010).

Tropical Cyclones and Societies: Projected Behavior

The past 30–40 years have seen a significant increase in the destructiveness of tropical cyclones globally. Although this increase cannot be attributed directly to anthropogenic climate change with certainty in every basin (Kossin, Olander, and Knapp 2013), the link between the recent rise in sea surface temperature and increasing tropical cyclone intensity has been thoroughly established (Elsner, Kossin, and Jagger 2008; Emanuel 2005). As global warming continues, sea surface temperature will continue to rise and a further increase in tropical cyclone intensity is probable (Holland and Bruyère 2014). In addition, a significant poleward shift of the maximum intensity of tropical cyclones has been detected over the last 30 years that is expected to continue under global

warming, potentially affecting regions with little or no tropical cyclone experience (Kossin, Emanuel, and Vecchi 2014; Kossin, Emanuel, and Camargo 2016). In addition, increasing exposure both of populations and assets will contribute to increasing destructiveness of tropical cyclones.

Variations in the El Niño Southern Oscillation (ENSO) are strongly tied to tropical cyclone activity globally. Although climate models have displayed some skill in simulating current ENSO variability (Vecchi et al. 2014), there is significant uncertainty around projected changes in the intensity and spatial pattern of ENSO, and consequently uncertainty about future tropical cyclone activity. Christensen et al. (2013) provide a synthesis of global and regional projections of tropical cyclone activity using a midrange climate scenario under an emissions scenario similar to A1B. They project a decrease in tropical cyclone numbers for the last 2 decades of this century by 5%–30% relative to 2000–2019, increases in the number of the strongest events by about 0%–25% and in their intensity by about 0%–5%, and increases in associated tropical cyclone rainfall intensities by 5%–20%. At the basin level, the global findings are confirmed for the WPO, the Southern Indian Ocean, and the Southern Pacific Ocean. Larger uncertainty exists for frequency in the North Indian Ocean, confirmed by a recent study that reflects subbasin characteristics and that finds a strong increase in tropical cyclone numbers by 46% for the Arabian Sea and a 31% decrease for the Bay of Bengal over this century (Murakami, Sugi, and Kitoh 2012).

Subbasin storm track characteristics are expected to change due to global warming. Current model projections, particularly for the second half of this century, must be interpreted with caution as the science is still unsettled. Several studies of the WPO show some agreement (Murakami, Wang, and Kitoh 2011; Wang, Wu, and Wang 2011; Yokoi, Takayabu, and Murakami 2013): tropical cyclone activity is expected to shift toward the central North Pacific, leading to less activity over Southeast Asia and in the South China Sea and resulting in enhanced activity in subtropical East Asia, for the eastern coast of central PRC, and eastern Japan.

⁷ Wind damage is proportional to the cube of peak sustained wind speed, making strong typhoons particularly destructive.

Skill in projecting tropical cyclone intensity using climate models, in particular at the subbasin scale, is currently limited by model resolution. The strongest and most damaging tropical cyclones can only be simulated at very fine resolution, which presently is only available in a few case studies. Findings presented thus far on future impacts are based on direct simulations of tropical cyclones in (global) climate models. This approach has known shortcomings, including incomplete representation of tropical cyclone intensity and frequency, due primarily to low model resolution (Walsh et al. 2016) and is useful in analyzing relative changes in tropical cyclone magnitude and number, as well as regional patterns of changing activity.

In contrast to direct simulations of tropical cyclones, dynamical downscaling techniques are used in order to overcome the resolution-related deficiencies of climate models identified. In this approach, tropical cyclones are either generated by climate models, detected, and then rerun using high-resolution hurricane models (see, e.g., Knutson et al. 2015), or tropical cyclones are artificially seeded and synthetic tracks are generated according to a wind field model that relies on wind data from climate models (Emanuel et al. 2006). Dynamical downscaling captures tropical cyclone intensity distributions more realistically (Knutson et al. 2015; Huang and Chan 2013; Colbert, Soden, and Kirtman 2015), although uncertainty remains with respect to absolute tropical cyclone numbers. The approach based on artificial seeding can be used to generate risk maps by generating thousands of synthetic tracks that allow for a statistical assessment of potential impacts and therefore seems favorable in determining country-specific vulnerability and adaptation potential.

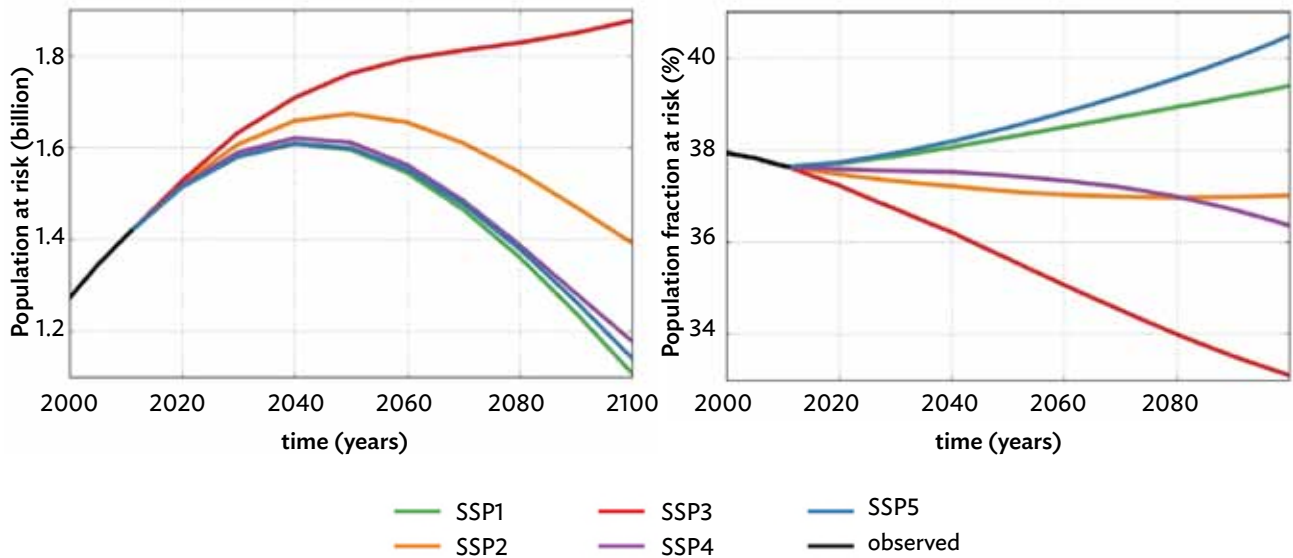
Anthropogenic climate change in combination with socioeconomic development will determine future losses from tropical cyclones. Inclusion of socioeconomic changes is therefore essential to quantify regions at high risk to monetary losses and fatalities. Different shared socioeconomic pathways (SSPs) have been developed that follow specific narratives and that are compatible with individual scenarios of global warming. These scenarios provide gridded population and income data through 2100 (Jones and O'Neill 2016; O'Neill et al. 2013) that are consistent with climate change mitigation and adaptation efforts. These explicit scenarios allow consistent impact estimates to be developed at the subnational scale without ad hoc assumptions.

Under all SSPs, the population at risk to tropical cyclones will increase toward the middle of the 21st century, reaching more than 1.6 billion people in Asia and the Pacific (see Figure 2.11). The population at risk is the sum of all people residing within 100 kilometers from the coastline and totaling more than 37% of the population in the Asia and Pacific region. Based on SSP-dependent inner-country development and migration, this fraction will change over this century and result in SSP-specific changes of the fraction of population at risk.

Several studies have started to estimate future tropical cyclone impacts by combining socioeconomic and tropical cyclone hazard projections. A sensitivity analysis has been conducted for the year 2050 assuming different levels of changes in tropical cyclone intensity and socioeconomic development, indicating the prominent role of socioeconomic changes on expected losses (Pielke 2007). Based on this study, however, no conclusions about the specific situation in the Asia and Pacific region can be drawn. The integrated assessment model FUND with an added damage function for tropical cyclones was used to study tropical cyclone impacts on economic growth up to 2100 (Narita, Tol, and Anthoff 2008). All studied areas see an increase in losses by 2100 with the United States and the PRC dominating in absolute terms. Annual losses relative to GDP are less than 0.01% for the PRC and Japan and higher in the small island states (about 0.04%). The use of integrated assessment models for the projection of the impacts of extreme events has been criticized as leading to a gross underestimation of losses (Stern 2013).

Based on insights from prior analyses of tropical cyclone losses in the United States, Mendelsohn et al. (2012) project global future tropical cyclone losses using dynamical downscaling methods, accounting for climatic as well as socioeconomic changes. They report both a doubling of annual tropical cyclone losses due to socioeconomic development and a doubling of losses expected due to climatic changes. In absolute terms, East Asia and North America will be most affected due to further accumulation of vulnerable assets and their proximity to the most intense tropical cyclones. This result, however, assumes fixed economic growth rates and is based on a tropical cyclone damage function derived for the United States only. Applicability to global tropical cyclone losses is debatable as it neglects substantial international differences in socioeconomic vulnerability.

Figure 2.11: Projected Population of Asia and the Pacific at Risk under Different Socioeconomic Scenarios



In addition to global studies, case studies have been conducted for specific countries. Based on a historic loss analysis using nightlight maps of the PRC coast, annual losses in the PRC for the upcoming decades are estimated to be \$0.5 billion (Elliott, Strobl, and Sun 2015). Esteban, Webersik, and Shibayama (2009) have conducted several case studies for countries in the Asia and Pacific region using Monte Carlo simulation that model the magnification of the tropical cyclone hazard by the year 2085. They estimate that the annual downtime of industry in Taipei, China could potentially double by 2085, leading to annual losses of 0.7% of national GDP. In 2085, Japan could suffer an overall productivity loss lowering GDP by 6%–13% (Esteban and Longarte-Galnares 2010), and the Philippines could suffer from a 17%–58% increase of direct damage to housing if adaptive measures are not taken (Esteban et al. 2013). In the case of Bangladesh, potential

tropical cyclone impacts, due largely to storm surges, are evaluated at roughly \$2.5 billion for an event with a 10-year return period, compared to estimated adaptation costs on the same magnitude until the year 2050 that could prevent most of the negative impacts (Dasgupta et al. 2010).

Some additional efforts have been taken to model the increasing risk from future storm surges caused by tropical cyclones, without explicitly quantifying associated losses (Lin and Emanuel 2015; Lin et al. 2012; Little et al. 2015; Nakamura et al. 2016). Consequent steps that bring together tropical cyclone hazard and SLR projections with socioeconomic development and that allow consistent projections of future tropical cyclone losses using innovative damage functions are still missing at present but will be critical in understanding future risk.

2.5 Changes in Hydrology

High Asia's Glaciers under Climate Change: Observations, Impacts, and Adaptation

High Mountain Asia (or High Asia) encompasses the largest accumulation of mountain glaciers in the world outside of Alaska and the polar regions. This vast mountainous region stretches from the Himalayan range in the south to the Tien Shan in the north forming a large east facing arch. The largest mountain ranges in order of glacier cover are the Himalayas (33,752 km²), Karakoram (15,629 km²), Tien Shan (12,815 km²), Pamirs (7,529 km²), and some smaller ranges (Dyurgerov 2010). Altogether, an area of 110,066 km² is covered by perennial ice distributed over about 82,000 glaciers with an estimate total volume of 12,807 cubic kilometers (Radić et al. 2013). This glaciated mountain region is the source of the largest and most important rivers of Asia, including the Indus, Ganges, Brahmaputra, Mekong, Yellow, Yangtze, Tarim, as well as the Amu and Syr Darya rivers. They are of irreplaceable importance to the people living in their catchments as their water resources provide irrigation, drinking water, hydropower generation, and industrial water, and they support the region's natural ecosystems. As many as 1.5 billion people live in these river basins, representing almost 20% of the world's population (Bolch et al. 2012; Immerzeel, van Beek, and Bierkens 2010). (Immerzeel et al. 2015; Bolch et al. 2012). Any changes in the hydrology at the source areas of those rivers may have substantial consequences for the downstream communities.

Glaciers are natural water reservoirs that respond to temperature, releasing water in summer and early autumn and capturing snow in the winter and in permanently frozen high altitudes. They are valuable buffers of climatic seasonality sustaining river flow during dry periods, although in most river basins of High Asia the precipitation season coincides with the melt season. The importance of the glacier melt decreases as the river descends into more rain-fed parts of the catchment, but in many cases such as the Indus, Amu Darya, Syr Darya, and the Tarim rivers, these downstream parts are arid and depend on snow and glacier melt to sustain flows. The large-scale climate systems influencing glaciers in High Asia are the Indian and Southeast Asian monsoon in the south and east (Himalayas) and the midlatitude westerlies in the Karakoram, Pamir, and Tien Shan mountain ranges (Kaser

et al. 2010; Maussion et al. 2013; Mölg, Maussion, and Scherer 2014). Changes to those climatic systems trigger responses in the glaciers leading to direct consequences for the water availability of downstream communities. For this reason, the behavior of glaciers has been used as a barometer for climate change (Haeberli et al. 2007).

Observed and projected changes to the glaciers of High Asia under climate change scenarios are discussed with reference to the potential impacts on the people depending on and living by the meltwater-fed rivers. This vast and inaccessible terrain has only received limited research, and many uncertainties remain. An overview of open research questions and important ongoing research is given with conclusions for adaptation strategies.

Observed Changes

Glaciers worldwide are in recession, as indicated by a limited but expanding network of monitoring sites (Zemp, Hoelzle, and Haeberli 2009). For the past 30–40 years, the availability of satellite imagery has enabled systematic assessments of the world's glaciers (Quincey and Bishop 2011), an ongoing effort that has been especially important for High Asia. Most glaciers are in decline, indicated by retreating fronts, shrinking ice cover, and volume losses, although changes are heterogeneous across the region (Bolch et al. 2012; Dyurgerov 2010; Farinotti et al. 2015; Sorg et al. 2012). While glacier area and volume losses are unequivocal in the Himalayas and Tien Shan, the Karakoram shows signs of stable or even advancing conditions. In the Himalayas, glacier area shrinkage varies in the range of 0.2%–0.7% per year from the 1960s to the early 2000s or 8%–28% over the 40 years. In the Tien Shan and Pamirs, rates are similar with 0.4%–0.8% per year in the northern edge and 0.2%–0.4% in the southern ranges.

A more important measure of glacier retreat is the mass loss expressed as negative mass balances (commonly expressed in average thickness change over the glacier area). In situ measurements are scarce and often short term, but most reference glaciers show mass losses varying 0.32–1.60 m per year in the Himalayas, 0.17–0.57 m in the Tien Shan, and 0.3 m per year in the Pamirs. Only in the Karakoram and parts of the Pamirs have signs of glacier advances been found (the so-called Karakoram anomaly) and the overall mass loss is comparatively low at 0.17–0.23 m per year (Fowler and Archer 2006; Gardelle, Berthier, and Arnaud 2012).

Hydrologists have also detected significant changes in the region's rivers with a tendency for increasing discharge associated with glaciological changes (Lutz et al. 2014). Causes for the increase are not only melting glaciers but predominantly increases in precipitation. Considerable research has focused on identifying the surplus meltwater, particularly in the dry catchments of High Asia (Duethmann et al. 2015). In the Tarim River, draining the mountain ranges surrounding the Taklamakan Desert, discharge has increased over the past 50 years (Krysanova et al. 2015; Tao et al. 2011), while in other rivers originating in the Tien Shan summer discharge may already be decreasing due to the disappearance of glacier cover (Hagg et al. 2007). Attribution of discharge changes is still limited by insufficient data at the basin scale, and integrated models are needed to decipher the various compensating factors.

Impacts under Climate Change

The general expectation for glaciated river basins is that increasing temperatures, often coupled with increasing precipitation, will initially result in increasing discharge, leading to benefits in the form of additional water supply, but potentially also to larger floods. Once glaciers have retreated, discharge will shift to rainfall-dominated regimes with lower meltwater peaks and higher sensitivity to precipitation. Quantifying this transition has been difficult, however. Projections of future trends in both glacier extent and river discharge are extremely scarce in the region (Chaturvedi et al. 2014) due to the scarcity and uncertainty in existing observations, particularly over the long term and at large scale. Existing climate change impact assessments are either highly uncertain, are local in scope, or only consider projected climate changes under a subset of RCP GHG scenarios. Additional uncertainty arises from general GCM simulations, most of which are not particularly good at simulating the Indian and Southeast Asian monsoon (Lutz et al. 2013). The urgent need for future assessments was highlighted in the Pontifical Academy of Sciences report on climate change (Kulkarni 2014) which reviews shortcomings of existing studies, many of which appear in Bolch et al. (2012).

Newly available glacier outlines for the Himalayan–Karakoram range were used to project future changes under the RCP8.5 and RCP2.6 scenarios based on

statistical relationships between glacier hypsometries, the equilibrium line altitudes, and their accumulation area (Chaturvedi et al. 2014). A broad order-of-magnitude estimate of future mass balances is projected until 2080. Current negative mass balances are set to increase sixfold with 27% of glacier shrinkage under the RCP8.5 scenario, while rates would “only” double with an area reduction of 11% under RCP2.6. This suggests that 16% of glacier area loss could be averted by following the aggressive emission targets of the RCP2.6 scenario.

In a global impact study investigating all glaciated regions, Radić et al. (2013) employed an ensemble of 14 GCMs to project glacier volume loss on glacier hypsometries and linear length–volume scaling. Covering the range of GCMs, they project volume losses for the RCP8.5 (RCP4.5) scenario over the 21st century.⁸ The eastern Himalayan glaciers may lose 70%–90% (20%–80%) of their mass, while in the western Himalayas, the Karakoram, and Hindu Kush losses may be in the range of 30%–85% (5%–80%). Glaciers north of the Himalayan–Karakoram range (Tien Shan, Pamirs, and Tibetan Plateau) may experience mass losses of 50%–85% (20%–80%). The large range of estimates reflects the great uncertainty associated with variation in GCM results, which is particularly large in mountainous terrain and in monsoon climates. While such large-scale results give a general idea of potential losses, they may fail to capture the heterogeneity of the region or particular river catchments.

At a localized scale, Immerzeel et al. (2012) simulate future changes in the small but highly glaciated Langtang catchment in the upper Ganges basin using a more physically based glacio-hydrological model. Strong increases in discharge are expected due both to temperature and precipitation increases. Under RCP8.5, a continuous decline in glacier area reaching 32% is projected until 2035 with a corresponding change in meltwater discharge. Since monsoon and melt seasons coincide, no shift in the river regime is expected.

Other assessments utilize projections based on historical behavior without reference to IPCC scenarios. Cogley (2011) extrapolates the observed rate of glacier shrinkage into the future for the Himalayan–Karakoram range. If

⁸ RCP4.5 is intermediate to the Paris-consensus scenario (RCP2.6) and the business-as-usual scenario (RCP8.5).

mass losses remain constant with those of 1975–2008, they conclude that glacier area and total mass would each decrease by about a half by 2035. If negative balances further increase as they have over 1975–2008, three-quarters would disappear. Hagg et al. (2007)(2007) tested the hydrological effects of both a 50% and a complete disappearance of glaciers in three catchments in the Tien Shan, projecting an earlier and increased meltwater peak. Although these findings are relevant to the specific catchments, they are not easily generalized to other catchments and are difficult to compare to other studies for confirmation.

Efforts are under way to integrate hydrological and glaciological changes at larger basin scales, but to date they rely on significant simplifications in the physical system and fall short of a systematic ensemble approach across all RCP scenarios. As examples, Immerzeel, van Beek, and Bierkens (2010)(2010) investigate climate change impacts in the largest rivers of High Asia using a coarse coupled glaciological and hydrological modeling framework. For the upper Indus, they project a decrease of 8.4% in discharge by 2050 under the Special Report on Emissions Scenarios (SRES) A1B scenario, a 17.6% decline for the upper Ganges and a 19.6% decline for the upper Brahmaputra (relative to 2000–2007). While these changes are severe, they would be even greater if they were not partially compensated for by increasing precipitation. A similar study using a more advanced and integrated glacio-hydrological model investigates changes in the same basins under two IPCC RCP scenarios until 2050 (Lutz et al. 2014). (Lutz et al. 2014) They project an increase in discharge of 2%–8% under the RCP8.5 ensemble in the upper Indus, 27% in the upper Ganges, and 1%–13% in the Brahmaputra. Although increasing glacier melt is a factor, the dominant driver of change is precipitation, with glacier melt declining around the middle of the century. These are important findings toward more integrated assessments, despite the large uncertainties.

The implications of projected changes for communities living by snow- and glacier-melt dominated rivers can be categorized as problems of water availability and of flooding. As glaciers recede, the reduced capacity of these natural reservoirs will necessarily lead to greater dependence on precipitation to sustain river flows (Immerzeel, van Beek, and Bierkens 2010). Warm and dry years in particular will experience significantly lower discharge with fewer glaciers present in the headwaters, with potentially severe

implications for reservoir operations, irrigated agriculture, thermal power plants, and drinking water systems. Reservoir operations and irrigated agriculture depend on strong summer floods and will subsequently depend on variable rain patterns. Reservoirs may run dry in the early growing season when water is most needed. Reduced summer floods would also lead to a loss of floodplain vegetation.

An increase in precipitation occurring as rain and less water stored as ice in the headwaters also increase flood risk, a natural hazard already claiming the most casualties in the Hindu Kush–Himalayan region (Shrestha et al. 2015). The combination of meltwater surplus and stronger precipitation, as many studies project, will lead to more severe floods, especially in warm and wet years. Another source of floodwaters is the growing number of glacial lakes appearing as glacier fronts recede (ICIMOD, Global Facility for Disaster Reduction and Recovery, and World Bank 2011; Shen et al. 2007). In Bhutan, India, Pakistan, Nepal, and the Ganges basin in the PRC, 8,790 glacial lakes were identified in the 1990s and 2000s, of which 204 were listed as prone to breaching, potentially triggering flash floods that destroy downstream communities.

While most studies are unable to accurately quantify these hazards on the regional scale, the patchwork of local studies in combination with coarser, large-scale assessments project severe changes for the catchments of High Asia under a warming climate. Increases in both precipitation and temperature lead to both greater risks of flooding and water scarcity. However, uncertainties remain high and systematic climate change assessments that cover all IPCC scenarios relevant for adaptation strategies are still absent for reasons of data availability and process understanding.

High Asia's Glaciers under Climate Change: Unresolved Issues

As the studies presented have shown, there is still considerable uncertainty associated with climate change impact assessments in High Asia. The uninhabited and inaccessible nature of the terrain and consequent lack of systematic observation is largely responsible, although socioeconomic and political factors are also critical. To reduce uncertainties, Bolch et al. (2012) suggest that efforts will need to be directed to the following research and infrastructure developments: (i) release a regionally

complete, up-to-date, and accurate glacier inventory; (ii) continue to develop and refine remote-sensing methods for estimating glacier changes; (iii) fill critical gaps in the climatic and hydrologic station network; (iv) continue existing mass-budget measurements on reference glaciers and establish new programs to cover more climate zones and glacier types in a more representative way, particularly in the Karakoram; (v) measure the thickness of selected glaciers as a basis for calibrating recently developed methods for modeling the subglacial topography and hence glacier volume; (vi) strengthen modeling efforts, in particular for climate projections, future glacier evolution, glacier lake outburst floods, and glacier runoff; and (vii) ensure field- and remote-sensing-based investigations consider the needs of these models and exchange all relevant data.

In general, precipitation remains the most uncertain environmental variable in High Asia. While most meteorological observations are from inhabited valley locations, the vast, inaccessible, and inhospitable higher altitudes remain virtually ungauged with only a sparse network of automatic weather stations operational. The emergence of reanalysis datasets has not been able to fill this data gap, although the High Asia Reanalysis dataset focusing on the region has improved prospects (Mausson et al. 2013). Immerzeel et al. (2015) show through inverse glacier mass balance and hydrological modeling that most datasets largely underestimate high elevation precipitation. In the Indus basin, annual precipitation sums are on average twice as high as recorded in meteorological stations and in extreme cases even up to 10 times as high. Filling those data gaps will have to be accomplished in part through more extensive observations but also through the integration of glaciological and hydrological observations in basin-scale modeling frameworks.

There are also gaps in the understanding of specific processes and their role in climate change impacts. The insulating effect of glaciers' debris cover in climate warming scenarios on a regional scale is still uncertain (Rowan et al. 2015; Scherler, Bookhagen, and Strecker 2011). While glacier shrinkage produces debris-covered glacier termini, it is uncertain by how much this dampening effect can reduce total disappearance. Regionally anomalous signs of glacier stability and isolated advancing fronts in the Karakoram are poorly understood (Rajbhandari et al. 2014). In addition to changes in climatic circulation, the

extremely steep terrain seems to favor glacier surge, that is, erratic and unusually fast advances. Capturing these local processes in regional-scale studies has so far been impossible.

In summary, research on the mountain hydrology of High Asia is limited by severe data scarcity preventing systematic, process, and scale-integrated assessments of climate change. Advances in glacier monitoring driven by advances in remote sensing and newly developed modeling approaches to overcome these data gaps offer opportunities for future assessments. Bringing together regional climate, glaciological, and hydrological models will be a key advantage.

Summary and Implications for Adaptation

Research on observed and projected changes of the glaciers of High Asia indicates a shift of snow and glacier melt-dominated river basins to more rain-fed regimes, which increases the water-related hazards for downstream communities. Loss of the natural snow and ice reservoirs and reliance on variable (albeit often increasing) precipitation may lead to water shortages in late summer or at the start of the growing season. In parallel, less precipitation detained as snow and ice as well as the growing number of glacial lakes increases the risk of disastrous flooding.

Adaptation strategies will need to address the loss of natural storage capacity by improving resilience to both water scarcity and flooding. The great uncertainties still attached to climate change impact assessments in the region call for flexible structural and nonstructural measures. The ongoing Himalayan Climate Change Adaptation Programme at the International Centre for Integrated Mountain Development is an example of research and advocacy of such approaches (Shrestha et al. 2015). The European Union-funded HighNoon project is another focusing on finding adaptation measures and improving available modeling approaches (Moors et al. 2011). Recommendations include more integrated, basin-scale assessments; early warning systems; and improved data collection and sharing. Combining development projects with adaptation strategies is also recommended through, for example, the implementation of building codes and land use planning. Whatever the eventual policies in the face of the large uncertainties may be, greater monitoring and cooperation will be important to combine all available data

and knowledge in more integrated modeling frameworks and decision support systems.

2.6 Flooding Risks in Asian River Basins

Flooding risks are usually defined as a function of hazard, exposure, and vulnerability (IPCC 2012; UNISDR 2011). Severity is often categorized in terms of number of affected people or economic damage. According to the International Disaster Database (EM-DAT), every year an average of 125 recorded riverine flood events occurred globally between 2001 and 2015, claiming a total of over 4,000 lives. Asia alone accounts for 90% of the reported affected people and 59% of economic losses worldwide, equivalent to about 80 million people and \$23 billion annually. Asian countries have also experienced the greatest recorded losses of life (India in 2013 with 6,373 deaths) and economic losses (Thailand in 2011 at \$40 billion) resulting from riverine flooding during 2001–2015 (EM-DAT 2016). The 2011 flood in Thailand was the most expensive insurance loss worldwide attributed to riverine flooding, with insured liabilities estimated at \$15 billion. Monsoonal flooding in Pakistan in 2010 caused nearly 2,000 immediate fatalities (Syvitski and Brakenridge 2013).

Under the IPCC definition (IPCC 2012), hazard refers to the “possible, future occurrence of natural or human-induced physical events that may have adverse effects on vulnerable and exposed elements;” exposure refers to the “inventory of elements in an area in which hazard events may occur;” and vulnerability refers to the “propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events.” Assessment of flood hazards, exposure, and risks has only recently been conducted at the global scale (Jongman, Ward, and Aerts 2012; Jongman et al. 2015; Pappenberger et al. 2012; Ward et al. 2013; Winsemius et al. 2013). Reported economic losses, adjusted for inflation, have more than tripled from \$7 billion to \$24 billion per year over the 1980–2011 period (Munich Re 2013), representing increasing flood risks due primarily to increases in flood exposure. Increasing exposure in turn is due primarily to the rapid population increase and economic development over this period. Rapid growth of population and of economic activity in Asian countries

are major contributors to the global increase in economic losses due to flooding during the past half century (IPCC 2012; UNISDR 2011; Visser et al. 2012).

No appreciable observed trend in the global flooding hazard has been reported, although increased variability was found in some Asian countries (Lim, Boochabun, and Ziegler 2012). Vulnerability has declined globally, especially in low-income countries, likely due to higher levels of adaptation measures which often accompany increases in per capita GDP (Jongman et al. 2015). Reported increases in flood risk may also be attributed to improvements in reporting (Peduzzi et al. 2009), urbanization in flood-prone areas, and progressive loss of awareness about natural risks (Kundzewicz et al. 2013).

Assessing Flooding Hazards

The flood hazard is influenced by many aspects of the climatic system, primarily precipitation characteristics including precipitation intensity, duration, amount, and timing, but also temperature-dependent processes including soil freezing, snow and ice formation and melting, and antecedent conditions in river basins such as soil moisture storage. Floods are also affected by preexisting drainage basin conditions resulting from a previous climate system; land surface characteristics such as soil and vegetation composition and structure and the rate of urbanization; and the presence of dikes, dams, and reservoirs (Bates et al. 2008; Kundzewicz et al. 2013). Urbanization in particular results in an increase in impermeable surface area within catchments, resulting in higher proportional rates of runoff.

In the Asian monsoon region, heavy precipitation is projected to increase, notably in Bangladesh and in the Yangtze River basin, because of the intensified convergence of water vapor flux in summer (Kundzewicz et al. 2013). Japanese GCM projections indicate that heavy precipitation is projected to increase substantially in South Asia (Kamiguchi et al. 2006). GCM projections also show an increase in flooding hazards in most humid Asian monsoon regions, due to increase in high intensity precipitation in much of South Asia and East Asia (Hirabayashi, Kanae, and Emori 2008).

Stream-gauge observations show increasing discharge trends over Southeast, Central, and Northeast Asia (Milly, Dunne, and Vecchia 2005). Generally increasing trends in

runoff (Milly, Dunne, and Vecchia 2005; Davie et al. 2013), flood frequency (Hirabayashi et al. 2013), and streamflow (Dankers et al. 2014; Koirala et al. 2014) are projected for the 21st century over much of South, Southeast, East, and Northeast Asia with good model agreement, while reduced runoff is projected in Central and West Asia (i.e., Afghanistan) by the end of the 21st century (Koirala et al. 2014). No significant change is observed and models are less certain on projected runoff changes over Eastern China (Milly, Dunne, and Vecchia 2005; Nohara et al. 2006), although flooding risk is projected to be much higher near the Tibetan Plateau (Milly et al. 2002), likely associated with snow and/or glacier melting under a warmer climate.

Despite high consistency between projections in parts of Asia, GCMs in general cannot adequately reproduce observed links between sea surface temperature anomalies and the strength of the South Asian monsoon, although some aspects of model skill have improved (Annamalai, Hamilton, and Sperber 2007; Sperber et al. 2013). At the country or local scale, the impact of climate change on river floods is generally less certain. For example, climate change may result in changes of between -37% and $+91\%$ in expected annual damage in Indonesia (Muis et al. 2015). While no significant trend in annual peak flows was found for the Ping basin in Thailand, there was a tendency for annual peak discharge fluctuations to be more extreme from the late 1960s (Lim, Boochabun, and Ziegler 2012).

In addition to long-term trends, flood hazards are also affected by quasiperiodic unforced oscillations of the ocean-atmosphere system. The probability of flooding in particular regions is related to El Niño or La Niña phases of the ENSO cycle (Ward et al. 2013). For example, during historical El Niño years, higher flood volumes are found for Central Asia, Bangladesh, and Papua New Guinea, while the flood volume is lower in regions such as central north PRC and Pakistan (Ward et al. 2014). By contrast, flood-causing tropical storms are more likely to affect Southeast Asia in La Niña years (Lim, Boochabun, and Ziegler 2012).

Most of the studies cited have focused on changes in natural streamflow. When anthropogenic influence on hydrology is included, relative changes in streamflow are expected to be even higher (Döll and Schmied 2012). Land cover changes in Southeast Asia may already have changed the regional monsoon flow patterns that affect hydro-climatology, including streamflow (Sen, Wang, and

Wang 2004). Widespread expansion of road networks may affect storm runoff peaks and dry-season flows in some catchments (Cuo and Giambelluca 2008). Dams and reservoir generally increase flood protection levels, which are generally low in Asia (Scussolini et al. 2016). Floods also contribute to siltation of reservoirs which over time limits the capacity of existing dams to control floods (Sanyal and Lu 2004).

Mapping Flood Hazard

Frequent and costly flooding events in Asia demand improved precision in identifying areas susceptible to inundation. Although dams, embankments, and other mitigation measures can reduce flood hazards, flood protection works are extremely expensive, requiring that regions at risk are properly identified. In Bangladesh, overbank flows and drainage congestion can result in inundation of 20% – 25% of the country's area in a normal year, while 100-year floods are projected to flood 60% of the total country's area (Kundzewicz et al. 2013). During the past 20 years, floods of such magnitude or higher occurred in 3 years (1987, 1988, and 1998) and inundated more than 60% of the country, suggesting that the 100-year flood under historical conditions may already have become more frequent (Kundzewicz et al. 2013). High resolution digital elevation models (DEMs) are however not widely available, and river discharge gauges remain relatively sparse in developing Asia, so the spatial extent of regions subject to flooding is difficult to delineate. Satellite remote sensing data combined with geographic information systems and DEMs can provide moderate resolution flood hazard maps that are useful tools, especially in developing Asia (Hagen and Lu 2011).

Recently, a global flood hazard map (Herold and Mouton 2011) has been produced for the 2011 Global Assessment Report on Disaster Risk Reduction, where statistical estimates have been merged with data from actual flood events observed by the Dartmouth Flood Observatory to derive maps indicating different return periods.⁹ This dataset is currently used by agencies around the world (UNISDR 2011) in reinsurance, large-scale flood preparedness, and emergency response and can also be used as a benchmark for future flood forecasting or climate impact assessment (Kappes et al. 2012).

In many Asian countries, flood hazard maps are not available at the national level. An exception is the

Afghanistan Flood Hazard Map (AFG-FHM) at a scale of 1:100,000, which is accessible to the public and scientific community and can be downloaded from the Civil–Military Overview website.⁹ The International Security Assistance Force (ISAF) and many government and aid agencies in Afghanistan are already using the AFG-FHM (Hagen and Lu 2011). National-scale flood hazard maps typically have higher accuracy and better detail than global flood hazard data. They can be used for insurance purposes or to inform domestic and international investment. For example, they can be used to identify priority regions where upgrading river defense structures has the greatest economic impact (Pappenberger et al. 2012).

Increasing Flooding Exposure

Locations of flooding exposure are identified by flood hazard mapping, which can involve a simple overlay of downscaled hazard and social economic data. The highest relative share of population and percentage of economy exposed to floods is found in Cambodia, Bangladesh, and Viet Nam (Peduzzi et al. 2009). Currently 75% of populations exposed to flooding globally live in Asia (Jongman, Ward, and Aerts 2012). Bangladesh encompasses the highest number of people exposed to floods, both in absolute and in relative terms, and ranks fourth in total assets exposed and second in relative share of assets exposed (Kundzewicz et al. 2013). The significant increase in flood exposure during the historical period is driven primarily by population increase and economic growth. Population and GDP are expected to continue to increase in Asia over the next decades. Using the World Bank's population and GDP projections, a relative increase of 370%–542% in value of Asian assets exposed to a 100-year flood was found, the highest of all continents in the world (Jongman, Ward, and Aerts 2012).

Yet, there are indications that population and assets exposed to floods have increased more rapidly than overall population or economic growth (Bouwer et al. 2007; Bouwer 2011; Jongman, Ward, and Aerts 2012). Using river network nightlights as a proxy for human exposure to floods, significant increases in flood exposure along rivers are found in most Asian countries, especially in Southeast Asia, at a rate faster than country-scale exposure. For

example, the consequences of the 2010 flood in the PRC can be reasonably linked to the 5.6% yearly increase of average nightlight intensity (a good proxy for human exposure to floods) along the PRC river networks (Ceola, Laio, and Montanari 2014). The continued expansion onto high-risk floodplain areas makes people and infrastructure more vulnerable to very large floods, especially when the designed flood defenses are unable to sustain unexpected flood volumes. Additionally, since the increases in exposure are so large, even if climate change were to reduce the severity of river floods, the overall impact will still likely be an increase in flood risk in Asia.

Changing Flooding Vulnerability

Flood risk awareness and the development of effective flood prevention strategies in developed countries typically reduce human losses due to flooding events (World Bank 2014). For instance, while total losses for a 100-year event in Mumbai could triple by the 2080s as compared with the present (Ranger et al. 2011), adaptation could help reduce future damages. Globally between 1980 and 2010, flooding vulnerability, represented by mortality and losses as a share of the population and GDP exposed to inundation, has declined, due in large extent to strong economic development in low-income countries (Jongman et al. 2015). Available studies on flooding vulnerability to date have been relatively limited, however. Flooding vulnerability can change from year to year, for example, due to people's changing perception and compensating measures after a disaster, and it can be influenced by random events. For example, the severity of the 2011 Thailand flooding was a result of the failure of flood control structures and systems that had effectively alleviated the damage from smaller events in the past. As a result of the uncertainty, there have been no data regarding future projections of flooding vulnerability globally or in Asia, and most of the previous studies assume constant vulnerability.

Flooding Risks in Asian River Basins: Future Research Directions

To manage increasing flood risks in developing Asia effectively, the problem of poor data quality must be addressed. Good hydrological data are essential in calibrating hydraulic models needed to simulate flooding

⁹ See: www.dartmouth.edu/floods/

¹⁰ See: https://www.cimicweb.org/_layouts/AFGFHM/index.html

dynamics. Improved density of stream gauge networks, measurement of flow velocities, and the timing and duration of flood events will allow better assessment of flooding risks. High resolution DEM data are also required. Globally, the current state-of-the-art DEM that is freely available and widely used in flood-related studies is Shuttle Radar Topography Mission (SRTM). SRTM has a vertical error in the range of 7 m, but the quality is much better for flat regions with <2 m error in most cases (Rodriguez, Morris, and Belz 2006). A vertical error of even 1 m in the DEM may lead to an error of hundreds of square kilometers in the estimated area vulnerable to flooding. Therefore, recognition of the magnitude of errors in the DEM is important in hydrological modeling (Sanyal and Lu 2004). The elevation is often overestimated due to land cover (e.g., forest or built environment), which will lead to an underestimation of flood extent (Baugh et al. 2013), particularly in tropical regions including Indonesia. Better flood hazard mapping based on improved DEMs will help with urban development and protection planning, which are essential in adapting to future flooding risks (Muis et al. 2015).

A number of recent studies summarized in this section of the report are based on simulation results from the ISIMIP project (Warszawski et al. 2014). The bias-corrected global climate simulation results provide improved future climate projections, which should also improve future flood projections. However, given available historical data, it is often necessary to estimate design flood events of up to 500-year return intervals on the basis of, for example, 30-

year periods of historical observation or simulation. Such estimates will most certainly be highly sensitive to fitting method and data outliers (e.g., Stedinger and Griffis 2011).

In 2016, the IPCC accepted the Paris invitation to provide a special report in 2018 on the impacts of global warming of 1.5°C above preindustrial levels and related global GHG emission pathways, calling for scientific assessments of the costs and benefits of low emission (mitigation) compared to high emission (no mitigation) scenarios. However, there is a general lack of research based on the Paris-consensus scenario (RCP2.6). Many current studies do not clarify the emission scenario(s) used, which are often middle-of-the-road scenarios. Both of these issues will likely be improved with the next stage ISIMIP simulations (known as ISIMIP2b; Frieler et al. 2016), which are designed to assess the impacts of a 1.5°C warming and provide a longer reporting period for more robust extreme statistics.

There are relatively few studies that examine human impact on flood hazards in Asia. One important reason is the lack of applicable global and/or regional data on factors such as management practices of dams and reservoirs, patterns of human water withdrawal, land subsidence, and so on. Recent efforts such as the global flood protection level database (Scussolini et al. 2016) call for community contribution for an accurate representation of the changing protection against natural flood hazards. Assessment on the flooding risks impact due to dam or reservoir construction, agricultural expansion, and urbanization is needed for the rapidly developing continent of Asia.

References—Part 2

- Alexander, L. V., et al. 2006. Global Observed Changes in Daily Climate Extremes of Temperature and Precipitation. *Journal of Geophysical Research*. 111.
- Allen, M. R., and W. J. Ingram. 2002 Constraints on Future Changes in Climate and the Hydrologic Cycle. *Nature*. 419(6903). pp. 224–232.
- Annamalai, H., K. Hamilton, and K. R. Sperber. 2007. The South Asian Summer Monsoon and Its Relationship with ENSO in the IPCC AR4 Simulations. *Journal of Climate*. 20(6). pp. 1071–1092.
- Bates, B., et al., eds. 2008. *Climate Change and Water*. IPCC Technical Paper of the Intergovernmental Panel on Climate Change (IPCC). Geneva: IPCC Secretariat.
- Baugh, C. A., et al. 2013. SRTM Vegetation Removal and Hydrodynamic Modeling Accuracy. *Water Resources Research*. 49(9). pp. 5276–5289.
- Bigano, A., et al. 2008. Economy-Wide Impacts of Climate Change: A Joint Analysis for Sea Level Rise and Tourism. *Mitigation and Adaptation Strategies for Global Change*. 13(8). pp. 765–791.
- Bolch, T., et al. 2012. The State and Fate of Himalayan Glaciers. *Science*. 336(6079). pp. 310–314.
- Bouwer, L. M. 2011. Have Disaster Losses Increased Due to Anthropogenic Climate Change? *Bulletin of the American Meteorological Society*. 92. pp. 39–46.
- Bouwer, L. M., et al. 2007. Confronting Disaster Losses. *Science*. 318. p. 753.
- Box, J. E., et al. 2012. Greenland Ice Sheet Albedo Feedback: Thermodynamics and Atmospheric Drivers. *Cryosphere*. 6(4). pp. 821–839.
- Brecht, H., et al. 2012. Sea-Level Rise and Storm Surges: High Stakes for a Small Number of Developing Countries. *The Journal of Environment & Development*. 21(1). pp. 120–138.
- Ceola, S., F. Laio, and A. Montanari. 2014. Satellite Nighttime Lights Reveal Increasing Human Exposure to Floods Worldwide. *Geophysical Research Letters*. 41(20). pp. 7184–7190.
- Chaturvedi, R. K., et al. 2014. Glacial Mass Balance Changes in the Karakoram and Himalaya Based on CMIP5 Multi-model Climate Projections. *Climatic Change*. 123. pp. 315–328.
- Chou, C., J. Y. Tu, and P. H. Tan. 2007. Asymmetry of Tropical Precipitation Change under Global Warming. *Geophysical Research Letters*. 34(17). pp. 1–5.
- Christensen, J. H., et al. 2013. Climate Phenomena and Their Relevance for Future Regional Climate Change. In *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press.
- Church, J. A., et al. 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. Cambridge, UK, and New York, NY: Cambridge University Press.
- Cogley, J. G. 2011. Present and Future States of Himalaya and Karakoram Glaciers. *Annals of Glaciology*. 52(59). pp. 69–73.
- Colbert, A. J., B. J. Soden, and B. P. Kirtman. 2015. The Impact of Natural and Anthropogenic Climate Change on Western North Pacific Tropical Cyclone Tracks. *Journal of Climate*. 28(5). pp. 1806–1823.
- Coumou, D., A. Robinson, and S. Rahmstorf. 2013. Global Increase in Record-Breaking Monthly-Mean Temperatures. *Climatic Change*. 118(3–4). pp. 771–782.
- Crompton, R. P., R. A. Pielke, Jr., and K. J. McAneney. 2011. Emergence Timescales for Detection of Anthropogenic Climate Change in US Tropical Cyclone Loss Data. *Environmental Research Letters*. 6(1). p. 14003.
- Cuo, L., and T. W. Giambelluca. 2008. The Roles of Roads and Agricultural Land Use in Altering Hydrological Processes in Nam Mae Rim Watershed, Northern Thailand. *Hydrological Processes*. 22(22). pp. 4339–4354.
- Dankers, R., et al. 2014. First Look at Changes in Flood Hazard in the Inter-Sectoral Impact Model Intercomparison Project Ensemble. *Proceedings of the National Academy of Sciences*. 111(9). pp. 3257–3261.
- Dasgupta, S., et al. 2010. *Vulnerability of Bangladesh to Cyclones in a Changing Climate. Potential Damages and Adaptation Cost*. Policy Research Working Paper 5280. Washington, DC: World Bank.
- Davie, J. C. S., et al. 2013. Comparing Projections of Future Changes in Runoff from Hydrological and Biome Models in ISI-MIP. *Earth System Dynamics*. 4(2). pp. 359–374.
- Deconto, R. M., and D. Pollard. 2016. Contribution of Antarctica to Past and Future Sea-Level Rise. *Nature*. 531. pp. 591–597.

- Döll, P., and H. M. Schmied. 2012. How Is the Impact of Climate Change on River Flow Regimes Related to the Impact on Mean Annual Runoff? A Global-Scale Analysis. *Environmental Research Letters*. 7(1).
- Domingues, C. M., et al. 2008. Improved Estimates of Upper-Ocean Warming and Multi-Decadal Sea-Level Rise. *Nature*. 453(7198). pp. 1090–1093.
- Duethmann, D., et al. 2015. Attribution of Streamflow Trends in Snow and Glacier Melt-Dominated Catchments of the Tarim River, Central Asia. *Water Resources Research*. 51(6). pp. 4727–4750.
- Dyurgerov, M. B. 2010. Reanalysis of Glacier Changes: From the IGY to the IPY, 1960–2008. *Materialy Glyatsiologicheskikh Issledovaniy*. 108. pp. 5–116.
- Elliott, R. J. R., E. Strobl, and P. Sun. 2015. The Local Impact of Typhoons on Economic Activity in China: A View from Outer Space. *Journal of Urban Economics*. 88. pp. 50–66.
- Elsner, J. B., J. P. Kossin, and T. H. Jagger. 2008. The Increasing Intensity of the Strongest Tropical Cyclones. *Nature*. 455. pp. 92–95.
- Emanuel, K. 2005. Increasing Destructiveness of Tropical Cyclones over the Past 30 Years. *Nature*. 436(7051). pp. 686–688.
- Emanuel, K., et al. 2006. A Statistical Deterministic Approach to Hurricane Risk Assessment. *Bulletin of the American Meteorological Society*. 87(3). pp. 299–314.
- Esteban, M., and G. Longarte-Galnares. 2010. Evaluation of the Productivity Decrease Risk Due to a Future Increase in Tropical Cyclone Intensity in Japan. *Risk Analysis*. 30(12). pp. 1789–1802.
- Esteban, M., C. Webersik, and T. Shibayama. 2009. Effect of a Global Warming-Induced Increase in Typhoon Intensity on Urban Productivity. *Sustainability Science*. 4(2). pp. 151–163.
- Esteban, M., et al. 2013. Global Warming and Tropical Cyclone Damage to Housing in the Philippines. *Climate Research*. 56(1). pp. 51–60.
- Estrada, F., W. J. W. Botzen, and R. S. J. Tol. 2015. Economic Losses from US Hurricanes Consistent with an Influence from Climate Change. *Nature Geoscience*. 8(11). pp. 880–884.
- Farinotti, D., et al. 2015. Substantial Glacier Mass Loss in the Tien Shan over the Past 50 Years. *Nature Geoscience*. 8(9). pp. 716–722.
- Fettweis, X., et al. 2013. Estimating Greenland Ice Sheet Surface Mass Balance Contribution to Future Sea Level Rise Using the Regional Atmospheric Climate Model MAR. *Cryosphere*. 7. pp. 469–489.
- Fischer, E. M., and R. Knutti. 2015. Anthropogenic Contribution to Global Occurrence of Heavy-Precipitation and High-Temperature Extremes. *Nature Climate Change*. 5. pp. 560–564.
- Fischer, E. M., U. Beyerle, and R. Knutti. 2013. Robust Spatially Aggregated Projections of Climate Extremes. *Nature Climate Change*. 3(12). pp. 1033–1038.
- Fowler, H. J., and D. R. Archer. 2006. Conflicting Signals of Climatic Change in the Upper Indus Basin. *Journal of Climate*. 19(17). pp. 4276–4293.
- Frieler, H. J., et al. 2013. Limiting Global Warming to 2°C Is Unlikely to Save Most Coral Reefs. *Nature Climate Change*. 3. pp. 165–170.
- Frieler, K., et al. 2016. Assessing the Impacts of 1.5°C Global Warming – Simulation Protocol of the Inter-Sectoral Model Intercomparison Project (ISIMIP2b). *Geoscientific Model Development*.
- Gardelle, J., E. Berthier, and Y. Arnaud. 2012. Slight Mass Gain of Karakoram Glaciers in the Early Twenty-First Century. *Nature Geoscience*. 5(5). pp. 322–325.
- Greenpeace. 2008. *Blue Alert: Climate Migrants in South Asia: Estimates and Solutions*. New Delhi: Greenpeace India Society.
- Gregory, J. M., et al. 2005. A Model Intercomparison of Changes in the Atlantic Thermohaline Circulation in Response to Increasing Atmospheric CO₂ Concentration. *Geophysical Research Letters*. 32(12). pp. 1–5.
- Gregory, J. M., et al. 2013. Twentieth-Century Global-Mean Sea Level Rise: Is the Whole Greater Than the Sum of the Parts? *Journal of Climate*. 26(13). pp. 4476–4499.
- Haerberli, W., et al. 2007. Integrated Monitoring of Mountain Glaciers as Key Indicators of Global Climate Change: The European Alps. *Annals of Glaciology*. 46(1). pp. 150–160.
- Hagen, E., and X. X. Lu. 2011. Let Us Create Flood Hazard Maps for Developing Countries. *Natural Hazards*. 58(3). pp. 841–843.
- Hagg, W., et al. 2007. Modelling of Hydrological Response to Climate Change in Glacierized Central Asian Catchments. *Journal of Hydrology*. 332(1–2). pp. 40–53.
- Hallegatte, S., et al. 2013. Future Flood Losses in Major Coastal Cities. *Nature Climate Change*. 3(9). pp. 802–806.
- Hansen, J., M. Sato, and R. Ruedy. 2012. Perception of Climate Change. *Proceedings of the National Academy of Sciences*. 109. pp. 14726–14727.

- Hanson, S., et al. 2011. A Global Ranking of Port Cities with High Exposure to Climate Extremes. *Climatic Change*. 104(1). pp. 89–111.
- Hempel, S., et al. 2013. A Trend-Preserving Bias Correction – The ISI-MIP Approach. *Earth System Dynamics*. 4(2). pp. 219–236.
- Herold, C., and F. Mouton. 2011. Global Flood Hazard Mapping Using Statistical Peak Flow Estimates. *Hydrology and Earth System Sciences*. 8(1). pp. 305–363.
- Hijioka, Y., et al. 2014. Regional Aspects. Chapter 24 – Asia. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press. pp. 1327–1370.
- Hinkel, J., and R. J. T. Klein. 2014. Integrating Knowledge to Assess Coastal Vulnerability to Sea-Level Rise: The Development of the DIVA Tool. *Global Environmental Change*. 19(3). pp. 384–395.
- Hirabayashi, Y., S. Kanae, and S. Emori. 2008. Global Projections of Changing Risks of Floods and Droughts in a Changing Climate. *Hydrological Sciences Journal*. 53(4). pp. 754–772.
- Hirabayashi, Y., et al. 2013. Global Flood Risk under Climate Change. *Nature Climate Change*. 3(9). pp. 816–821.
- Ho, C.-H., et al. 2004. Interdecadal Changes in Summertime Typhoon Tracks. *Journal of Climate*. 17. pp. 1767–1776.
- Holland, G., and C.L. Bruyère. 2014. Recent Intense Hurricane Response to Global Climate Change. *Climate Dynamics*. 42. pp. 617–627.
- Howat, I. M., et al. 2010. Seasonal Variability in the Dynamics of Marine-Terminating Outlet Glaciers in Greenland. *Journal of Glaciology*. 56(198). pp. 601–613.
- Huang, W.-R., and J. C. L. Chan. 2013. Dynamical Downscaling Forecasts of Western North Pacific Tropical Cyclone Genesis and Landfall. *Climate Dynamics*. 42(7–8). pp. 2227–2237.
- Hung, C., X. Liu, and M. Yanai. 2004. Symmetry and Asymmetry of the Asian and Australian Summer Monsoons. *Journal of Climate*. 17(12). pp. 2413–2426.
- Hunt, A., and P. Watkiss. 2011. Climate Change Impacts and Adaptation in Cities: A Review of the Literature. *Climatic Change*. 104(1). pp. 13–49.
- Immerzeel, W. W., L. P. H. van Beek, and M. F. P. Bierkens. 2010. Climate Change Will Affect the Asian Water Towers. *Science*. 328(5984). pp. 1382–1385.
- Immerzeel, W. W., et al. 2012. Hydrological Response to Climate Change in a Glacierized Catchment in the Himalayas. *Climatic Change*. 110(3–4). pp. 721–736.
- Immerzeel, W. W., et al. 2015. Reconciling High-Altitude Precipitation in the Upper Indus Basin with Glacier Mass Balances and Runoff. *Hydrology and Earth System Sciences*. 19(11). pp. 4673–4687.
- Intergovernmental Panel on Climate Change (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. Cambridge, UK, and New York, NY: Cambridge University Press.
- . 2013. *Climate Change 2013: The Physical Science Basis*. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press.
- International Centre for Integrated Mountain Development (ICIMOD), Global Facility for Disaster Reduction and Recovery, and World Bank. 2011. *Glacial Lakes and Glacial Lake Outburst Floods in Nepal*. Kathmandu: ICIMOD.
- International Disaster Database (EM-DAT). 2016. The OFDA/CRED International Disaster Database 2016. Universite Catholique de Louvain. Brussels, Belgium. <http://www.emdat.be>
- Jevrejeva, S., J. C. Moore, and A. Grinsted. 2010. How Will Sea Level Respond to Changes in Natural and Anthropogenic Forcings by 2100? *Geophysical Research Letters*. 37(7). pp. 1–5.
- Jones, B., and B. O’Neill. 2016. Spatially Explicit Global Population Scenarios for the Shared Socioeconomic Pathways. *Environmental Research Letters*. 11(8).
- Jongman, B., P. J. Ward, and J. C. Aerts. 2012. Global Exposure to River and Coastal Flooding: Long Term Trends and Changes. *Global Environmental Change*. 22(4). pp. 823–835.
- Jongman, B., et al. 2015. Declining Vulnerability to River Floods and the Global Benefits of Adaptation. *Proceedings of the National Academy of Sciences*. 112(18). pp. E2271–E2280.
- Kamiguchi, K., et al. 2006. Changes in Precipitation-Based Extremes Indices Due to Global Warming Projected by a Global 20-Km-Mesh Atmospheric Model. *SOLA*. 2. pp. 64–67.

- Kang, N.-Y., and J.B. Elsner. 2012. Consensus on Climate Trends in Western North Pacific Tropical Cyclones. *Journal of Climate*. 25(21). pp. 7564–7573.
- . 2015. Trade-Off between Intensity and Frequency of Global Tropical Cyclones. *Nature Climate Change*. 5. pp. 661–664.
- Kappes, M. S., et al. 2012. The MultiRISK Platform: The Technical Concept and Application of a Regional-Scale Multihazard Exposure Analysis Tool. *Geomorphology*. 151–152. pp. 139–155.
- Kaser, G., et al. 2010. Contribution Potential of Glaciers to Water Availability in Different Climate Regimes. *Proceedings of the National Academy of Sciences*. 107(47). pp. 21300–21305.
- Knapp, K. R., et al. 2010. Unifying Tropical Cyclone Data. *The International Best Track Archive for Climate Stewardship*. pp. 363–376.
- Knutson, T. R., et al. 2010. Tropical Cyclones and Climate Change. *Nature Geoscience*. 3. pp. 157–163.
- Knutson, T. R., et al. 2015. Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios. *Journal of Climate*. 28. pp. 7203–7224.
- Koirala, S., et al. 2014. Global Assessment of Agreement among Streamflow Projections Using CMIP5 Model Outputs. *Environmental Research Letters*. 9(6).
- Kopp, R. E., et al. 2016. Temperature-Driven Global Sea-Level Variability in the Common Era. *Proceedings of the National Academy of Sciences*. 113(11). pp. E1434–E1441.
- Kossin, J. P., T. L. Olander, and K.R. Knapp. 2013. Trend Analysis with a New Global Record of Tropical Cyclone Intensity. *Journal of Climate*. 26(24). pp. 9960–9976.
- Kossin, J. P., K. A. Emanuel, and G. A. Vecchi. 2014. The Poleward Migration of the Location of Tropical Cyclone Maximum Intensity. *Nature*. 509(7500). pp. 349–352.
- Kossin, J. P., K. A. Emanuel, and S. J. Camargo. 2016. Past and Projected Changes in Western North Pacific Tropical Cyclone Exposure. *Journal of Climate*. 29(16). pp. 5725–5739.
- Krishna Kumar, K., et al. 2004. Climate Impacts on Indian Agriculture. *International Journal of Climatology*. 24(11). pp. 1375–1393.
- Krysanova, V., et al. 2015. Analysis of Current Trends in Climate Parameters, River Discharge and Glaciers in the Aksu River Basin (Central Asia). *Hydrological Sciences Journal*. 60(4). pp. 566–590.
- Kulkarni, A. V. 2014. Glaciers as Source of Water: The Himalaya. Sustainable Humanity, Sustainable Nature: Our Responsibility. Joint Workshop of the Pontifical Academy of Sciences and the Pontifical Academy of Social Sciences, 2–6 May.
- Kundzewicz, Z. W., et al. 2013. Flood Risk and Climate Change: Global and Regional Perspectives. *Hydrological Sciences Journal*. 59(1). pp. 1–28.
- Le, T. V. H., et al. 2007. The Combined Impact on the Flooding in Vietnam's Mekong River Delta of Local Man-Made Structures, Sea Level Rise, and Dams Upstream in the River Catchment. *Estuarine, Coastal, and Shelf Science*. 71(1–2). pp. 110–116.
- Lehmann, J., and D. Coumou. 2015. The Influence of Mid-Latitude Storm Tracks on Hot, Cold, Dry and Wet Extremes. *Scientific Reports*. 5.
- Lehmann, J., D. Coumou, and K. Frieler. 2015. Increased Record-Breaking Precipitation Events under Global Warming. *Climatic Change*. 132. pp. 501–515.
- Levermann, A., et al. 2005. Dynamic Sea Level Changes Following Changes in the Thermohaline Circulation. *Climate Dynamics*. 24(4). pp. 347–354.
- Levermann, A., et al. 2009. Basic Mechanism for Abrupt Monsoon Transitions. *Proceedings of the National Academy of Sciences*. 106(49). pp. 20572–20577.
- Levermann, A., et al. 2013. The Multimillennial Sea-Level Commitment of Global Warming. *Proceedings of the National Academy of Sciences*. 110(34). pp. 13745–13750.
- Levermann, A., et al. 2014. Projecting Antarctic Ice Discharge Using Response Functions from SeaRISE Ice-Sheet Models. *Earth System Dynamics*. 5(2). pp. 271–293.
- Lim, H. S., K. Boochabun, and A.D. Ziegler. 2012. Modifiers and Amplifiers of High and Low Flows on the Ping River in Northern Thailand (1921–2009): The Roles of Climatic Events and Anthropogenic Activity. *Water Resources Management*. 26(14). pp. 4203–4224.
- Lin, N., and K. Emanuel. 2015. Grey Swan Tropical Cyclones. *Nature Climate Change*. 6(1). pp. 106–111.
- Lin, N., et al. 2012. Physically Based Assessment of Hurricane Surge Threat under Climate Change. *Nature Climate Change*. 2(6). pp. 462–467.
- Little, C. M., et al. 2015. Joint Projections of US East Coast Sea Level and Storm Surge. *Nature Climate Change*. 5. pp. 1114–1120.

- Lutz, A. F., et al. 2014. Consistent Increase in High Asia's Runoff Due to Increasing Glacier Melt and Precipitation. *Nature Climate Change*. 4(7). pp. 587–592.
- Lutz, R., et al. 2013. Characterizing the Development of Sectoral Gross Domestic Product Composition. *Physical Review E*. 88(1). pp. 1–7.
- Marfai, M. A., and L. King. 2008. Potential Vulnerability Implications of Coastal Inundation due to Sea Level Rise for the Coastal Zone of Semarang City, Indonesia. *Environmental Geology*. 54(6). pp. 1235–1245.
- Marzeion, B., and A. Levermann. 2014. Loss of Cultural World Heritage and Currently Inhabited Places to Sea-Level Rise. *Environmental Research Letters*. 9(3).
- Marzeion, B., et al. 2014. Attribution of Global Glacier Mass Loss to Anthropogenic and Natural Causes. *Science*. 345(6199). pp. 919–921.
- Maussion, F., et al. 2013. Precipitation Seasonality and Variability over the Tibetan Plateau as Resolved by the High Asia Reanalysis. *Journal of Climate*. 27(5). pp. 1910–1927.
- McLeod, E., et al. 2010. Sea-Level Rise Vulnerability in the Countries of the Coral Triangle. *Sustainability Science*. 5(2). pp. 207–222.
- Mendelsohn, R., et al. 2012. The Impact of Climate Change on Global Tropical Cyclone Damage. *Nature Climate Change*. 2(3). pp. 205–209.
- Mengel, M., et al. 2016. Future Sea Level Rise Constrained by Observations and Long-Term Commitment. *Proceedings of the National Academy of Sciences*. 113. pp. 2597–2602.
- Menon, A., et al. 2013. Consistent Increase in Indian Monsoon Rainfall and Its Variability across CMIP-5 Models. *Earth System Dynamics*. 4(2). pp. 287–300.
- Milly, P. C. D., et al. 2002. Increasing Risk of Great Floods in a Changing Climate. *Nature*. 415(6871). pp. 514–517.
- Milly, P. C. D., K. A. Dunne, and A. V. Vecchia. 2005. Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate. *Nature*. 438(7066). pp. 347–350.
- Mitrovica, J. X., et al. 2001. Recent Mass Balance of Polar Ice Sheets Inferred from Patterns of Global Sea-Level Change. *Nature*. 409(6823). pp. 1026–1029.
- Mölg, T., F. Maussion, and D. Scherer. 2014. Mid-Latitude Westerlies as a Driver of Glacier Variability in Monsoonal High Asia. *Nature Climate Change*. 4(1). pp. 68–73.
- Moors, E. J., et al. 2011. Adaptation to Changing Water Resources in the Ganges Basin, Northern India. *Environmental Science Policy*. 14(7). pp. 758–769.
- Moss, R. H., et al. 2010. The Next Generation of Scenarios for Climate Change Research and Assessment. *Nature*. 463(7282). pp. 747–56.
- Muis, S., et al. 2015. Flood Risk and Adaptation Strategies under Climate Change and Urban Expansion: A Probabilistic Analysis Using Global Data. *Science of the Total Environment*. 538. pp. 445–457.
- Munich Re. 2013. Munich Reinsurance Company Geo Risks Research, 148 [online]. http://www.munichre.com/publications/302-07807_en.pdf
- Murakami, H., B. Wang, and A. Kitoh. 2011. Future Change of Western North Pacific Typhoons: Projections by a 20-Km-Mesh Global Atmospheric Model. *Journal of Climate*. 24(4). pp. 1154–1169.
- Murakami, H., M. Sugi, and A. Kitoh. 2012. Future Changes in Tropical Cyclone Activity in the North Indian Ocean Projected by High-Resolution MRI-AGCMs. *Climate Dynamics*. 40(7–8). pp. 1949–1968.
- Nakamura, R., et al. 2016. Future Typhoon and Storm Surges under Different Global Warming Scenarios: Case Study of Typhoon Haiyan (2013). *Natural Hazards*. 82(3). pp. 1645–1681.
- Narita, D., R. S. J. Tol, and D. Anthoff. 2008. *Damage Costs of Climate Change through Intensification of Tropical Cyclone Activities: An Application of FUND*. ESRI Working Papers. No. 259.
- Neumann, B., et al. 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. *PLoS One*. 10(3).
- Nohara, D., et al. 2006. Impact of Climate Change on River Discharge Projected by Multimodel Ensemble. *Journal of Hydrometeorology*. 7(5). pp. 1076–1089.
- Noy, I. 2016. Tropical Storms: The Socio-economics of Cyclones. *Nature Climate Change*. 6(4). pp. 343–345.
- O'Neill, B. C., et al. 2013. A New Scenario Framework for Climate Change Research: The Concept of Shared Socioeconomic Pathways. *Climatic Change*. 122(3). pp. 387–400.
- Pall, P., M. R. Allen, and D. A. Stone. 2007. Testing the Clausius–Clapeyron Constraint on Changes in Extreme Precipitation under CO₂ Warming. *Climate Dynamics*. 28(4). pp. 351–363.
- Pappenberger, F., et al. 2012. Deriving Global Flood Hazard Maps of Fluvial Floods through a Physical Model

- Cascade. *Hydrology and Earth Systems Sciences*. 16(11). pp. 4143–4156.
- Peduzzi, P., et al. 2009. Assessing Global Exposure and Vulnerability towards Natural Hazards: The Disaster Risk Index. *Natural Hazards and Earth System Sciences*. 9. pp. 1149–1159.
- Pielke Jr., R. A. 2007. Future Economic Damage from Tropical Cyclones: Sensitivities to Societal and Climate Changes. *Philosophical Transactions of the Royal Society A*. 365(1860). pp. 2717–2729.
- Quincey, D. J., and M. P. Bishop. 2011. Optical Remote Sensing of Alpine Glaciers. In V. P. Singh, P. Singh, and U. K. Haritashya, eds. *Encyclopedia of Snow, Ice and Glaciers*. Netherlands: Springer.
- Radić, V., et al. 2013. Regional and Global Projections of Twenty-First Century Glacier Mass Changes in Response to Climate Scenarios from Global Climate Models. *Climate Dynamics*. 42(1–2). pp. 37–58.
- Rahmstorf, S. 2006. A Semi-empirical Approach to Projecting Future Sea Level Rise. *Science*. 315(5810). pp. 368–370.
- Rahmstorf, S., et al. 2015. Exceptional Twentieth-Century Slowdown in Atlantic Ocean Overturning Circulation. *Nature Climate Change*. 5(5). pp. 475–480.
- Rajbhandari, R., et al. 2014. Projected Changes in Climate over the Indus River Basin Using a High Resolution Regional Climate Model (PRECIS). *Climate Dynamics*. 44(1–2). pp. 339–357.
- Ranger, N., et al. 2011. An Assessment of the Potential Impact of Climate Change on Flood Risk in Mumbai. *Climatic Change*. 104(1). 139–167.
- Ranson, M., et al. 2014. Tropical and Extratropical Cyclone Damages under Climate Change. *Climatic Change*. 127(2). pp. 227–241.
- Rodriguez, E., C. S. Morris, and J. E. Belz. 2006. A Global Assessment of the SRTM Performance. *Photogrammetric Engineering and Remote Sensing*. 72(3). pp. 249–260.
- Rowan, A. V., et al. 2015. Modelling the Feedbacks between Mass Balance, Ice Flow and Debris Transport to Predict the Response to Climate Change of Debris-Covered Glaciers in the Himalaya. *Earth and Planetary Science Letters*. 430. pp. 427–438.
- Sanyal, J., and X.X. Lu. 2004. Application of Remote Sensing in Flood Management with Special Reference to Monsoon Asia: A Review. *Natural Hazards*. 33(2). pp. 283–201.
- Sardeshmukh, P. D., G. P. Compo, and C. Penland. 2015. Need for Caution in Interpreting Extreme Weather Statistics. *Journal of Climate*. 28. pp. 9166–9187.
- Scherler, D., B. Bookhagen, and M. R. Strecker. 2011. Spatially Variable Response of Himalayan Glaciers to Climate Change Affected by Debris Cover. *Nature Geoscience*. 4(3). pp. 156–159.
- Scussolini, P., et al. 2016. FLOPROS: An Evolving Global Database of Flood Protection Standards. *Natural Hazards and Earth Systems Sciences*. 16(5). pp. 1049–1061.
- Sen, O. L., Y. Wang, and B. Wang. 2004. Impact of Indochina Deforestation on the East Asian Summer Monsoon. *Journal of Climate*. 17(6). pp. 1366–1380.
- Shen, Y., et al. 2007. Response of Glacier Flash Flood to Climate Warming in the Tarim River Basin. *Advances in Climate Change Research*. 3 (Suppl.). pp. 51–56.
- Sherwood, S. C., and M. Huber. 2010. An Adaptability Limit to Climate Change Due to Heat Stress. *Proceedings of the National Academy of Sciences*. 107(21). pp. 9552–9555.
- Shrestha, A., et al. 2015. *The Himalayan Climate and Water Atlas: Impact of Climate Change on Water Resources in Five of Asia's Major River Basins*. ICIMOD, GRID-Arendal and CICERO. Kathmandu, Nepal: International Centre for Integrated Mountain Development.
- Sillmann, J., et al. 2013a. Climate Extremes Indices in the CMIP5 Multimodel Ensemble: Part 1. Model Evaluation in the Present Climate. *Journal of Geophysical Research: Atmospheres*. 118(4). pp. 1716–1733.
- . 2013b. Climate Extremes Indices in the CMIP5 Multimodel Ensemble: Part 2. Future Climate Projections. *Journal of Geophysical Research: Atmospheres*. 118(6). pp. 2473–2493.
- Singh, O. P. 2010. Recent Trends in Tropical Cyclone Activity in the North Indian Ocean. In Y. Charabi, ed. *Indian Ocean Tropical Cyclones and Climate Change*. Dordrecht: Springer Netherlands.
- Slangen, A. B. A., et al. 2014. Projecting Twenty-First Century Regional Sea-Level Changes. *Climatic Change*. 124(1–2). pp. 317–332.
- Sorg, A., et al. 2012. Climate Change Impacts on Glaciers and Runoff in Tien Shan (Central Asia). *Nature Climate Change*. 2(10). pp. 725–731.
- Sperber, K. R., et al. 2013. The Asian Summer Monsoon: An Intercomparison of CMIP5 vs. CMIP3 Simulations of the Late 20th Century. *Climate Dynamics*. 41(9–10). pp. 2711–2744.

- Stedinger, J. R., and V.W. Griffis. 2011. Getting from Here to Where? Flood Frequency Analysis and Climate. *Journal of the American Water Resources Association*. 47(3). pp. 506–513.
- Stern, N. 2013. The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*. III(51). pp. 331–362.
- Syvitski, J., and G. Brakenridge. 2013. Causation and Avoidance of Catastrophic Flooding along the Indus River, Pakistan. *GSA Today*. 23(1). pp. 4–10.
- Tao, F., et al. 2004. Variability in Climatology and Agricultural Production in China in Association with the East Asian Summer Monsoon and El Niño Southern Oscillation. *Climate Research*. 28. pp. 23–30.
- Tao, H., et al. 2011. Trends of Streamflow in the Tarim River Basin during the Past 50 Years: Human Impact or Climate Change? *Journal of Hydrology*. 400(1–2). pp. 1–9.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*. 93(4). pp. 485–498.
- Trenberth, K. 2011. Changes in Precipitation with Climate Change. *Climate Research*. 47(1). pp. 123–138.
- United Nations Office for Disaster Risk Reduction (UNISDR). 2011. *Global Assessment Report on Disaster Risk Reduction: Revealing Risk, Redefining Development*. Geneva.
- van den Broeke, M. R., et al. 2011. Ice Sheets and Sea Level: Thinking Outside the Box. *Surveys in Geophysics*. 32(4–5). pp. 495–505.
- Vecchi, G. A., et al. 2014. On the Seasonal Forecasting of Regional Tropical Cyclone Activity. *Journal of Climate*. 27(21). pp. 7994–8016.
- Vermeer, M., and S. Rahmstorf. 2009. Global Sea Level Linked to Global Temperature. *Proceedings of the National Academy of Sciences*. 106(51). pp. 21527–21532.
- Visser, H., et al. 2012. *Weather-Related Disasters: Past, Present and Future*. PBL Netherlands Environmental Assessment Agency.
- Walsh, K. J. E., et al. 2016. Tropical Cyclones and Climate Change. *Wiley Interdisciplinary Reviews: Climate Change*. 7(1). pp. 65–89.
- Wang, R., L. Wu, and C. Wang. 2011. Typhoon Track Changes Associated with Global Warming. *Journal of Climate*. 24(14). pp. 3748–3752.
- Ward, P. J., et al. 2013. Assessing Flood Risk at the Global Scale: Model Setup, Results, and Sensitivity. *Environmental Research Letters*. 8(4).
- Ward, P. J., et al. 2014. Strong Influence of El Niño Southern Oscillation on Flood Risk around the World. *Proceedings of the National Academy of Sciences*. 111(44). pp. 15659–15664.
- Warszawski, L., et al. 2014. The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project Framework. *Proceedings of the National Academy of Sciences*. 111(9). pp. 3228–3232.
- Westra, S., L. V. Alexander, and F. W. Zwiers. 2013. Global Increasing Trends in Annual Maximum Daily Precipitation. *Journal of Climate*. 26(11). pp. 3904–3918.
- Westra, S., et al. 2014. Future Changes to the Intensity and Frequency of Short-Duration Extreme Rainfall. *Review of Geophysics*. 52. pp. 522–555.
- Winkelmann, R., et al. 2015. Combustion of Available Fossil Fuel Resources Sufficient to Eliminate the Antarctic Ice Sheet. *Scientific Advances*. 1(8).
- Winsemius, H. C., et al. 2013. A Framework for Global River Flood Risk Assessments. *Hydrology and Earth System Sciences*. 17(5). pp. 1871–1892.
- World Bank. 2014. *Urban Development*. <http://www.worldbank.org/en/topic/urbandevelopment> (accessed 17 April 2016).
- Wu, L. and H. Zhao. 2012. Dynamically Derived Tropical Cyclone Intensity Changes over the Western North Pacific. *Journal of Climate*. 25(1). pp. 89–98.
- Yokoi, S., Y. N. Takayabu, and H. Murakami. 2013. Attribution of Projected Future Changes in Tropical Cyclone Passage Frequency over the Western North Pacific. *Journal of Climate*. 26(12). pp. 4096–4111.
- Zemp, M., M. Hoelzle, and W. Haeberli. 2009. Six Decades of Glacier Mass-Balance Observations: A Review of the Worldwide Monitoring Network. *Annals of Glaciology*. 50(50). pp. 101–111.
- Zhang, D. D., et al. 2007. Global Climate Change, War, and Population Decline in Recent Human History. *Proceedings of the National Academy of Sciences*. 104(49). pp. 19214–19219.



**CLIMATE CHANGE IMPACTS ON HUMAN
SYSTEMS IN ASIA AND THE PACIFIC**



This section of the report presents, summarizes, and discusses the status of the literature pertaining to expected impacts of climate change on selected human systems.

3.1 Climate Change: Agriculture and Marine Ecosystems

Agriculture

Agriculture significantly contributes to the GDP of some of the larger countries of the Asia and Pacific region, and employs a large part of the population in many developing member countries.¹ Declining soil productivity, groundwater depletion, and declining water availability, as well as increased pest incidence and salinity threaten the sustainability and food security in the region (Wassmann et al. 2009b). Projected changes in climate will significantly add to these stressors.

Future Changes in Land Productivity and Crop Yields in South Asia and Southeast Asia

Climate change is projected to strongly impact agricultural production, the development of the sector, and the economic benefits derived from it (Nelson et al. 2009). Climatic changes occur in an already complex water–agriculture nexus in the region characterized by (i) agriculture being the main reason for freshwater extraction in many countries,² (ii) large areas being rainfed agriculture,³ and (iii) groundwater being a major water source, especially for irrigation in South Asia (Shah 2009).

Earlier assessments of climate impacts on agriculture in South Asia and Southeast Asia have shown that, despite regional variations, both biophysical climate impacts as well as ensuing impacts on development are likely to be substantial (Hijioka et al. 2014; World Bank 2013b; Schellnhuber et al. 2014; Vinke et al. 2016).

Estimates from global crop model intercomparisons show median maize and wheat yield changes to be

adversely impacted in Southeast Asia and South Asia under the RCP8.5 scenario (increase in temperature of approximately 3.5°C–4°C) toward the end of the 21st century (Rosenzweig et al. 2013). Crop yield may increase in the northern areas of the region. Median yields in rice and soy are projected to decrease in the Ganges region and Thailand but increase in most of the rest of the region.

Increasing temperatures and changing precipitation levels are important drivers of changing crop productivity in South Asia and Southeast Asia, compounded by the effects of increasing atmospheric CO₂ concentrations, partly counteracting negative climatic effects. However, in the longer term, the negative impacts of increases in temperatures beyond 2°C on rice and wheat yields in South Asia would not be offset by CO₂ fertilization effects (Lal 2011). Instead, cereal production is expected to decline by 4%–10% under a regional warming of 3°C by the end of this century (Lal 2011). Moreover, South Asia's agriculture is affected by climate change under a global mean warming of about 1.8°C–2°C above preindustrial levels by 2050—especially when the potential benefits of the CO₂ fertilization effect are not included (Nelson et al. 2009, 2010b). In a review of 52 original studies, Knox et al. (2012) estimate a mean change in yield of all crops by approximately 8% by 2050 in South Asia, including a yield reduction of 16% for maize and 11% for sorghum.

In Bangladesh, yield reductions in rice and wheat due to coastal flooding vary from 0% when floods partly submerge the plants for a few days to 100% when floods submerge most of the plant for a period longer than 15 days no matter the stage of plant development (Yu et al. 2010). Moreover, in the southern region of Bangladesh, large amounts of productive land could be affected by sea-level rise, with 40% area losses projected for a 65 cm rise by the 2080s (Yu et al. 2010). In combination with changes in temperature of about 2°C and slightly increasing precipitation in 2050 compared to preindustrial levels and the benefits of CO₂ fertilization, mean changes in floods and inundation as well as rising sea levels might cause an approximately 80-million-ton cumulative reduction in rice

¹ For example, agriculture contributed to 18% of GDP in India, 25% in Pakistan, and 27% in Tajikistan in 2014. The sector contributed to 60% of female and 43% of male employment in India in 2014 (World Bank 2016).

² For example, agriculture represents 98% in Nepal, 94% in Pakistan, 94% in Bhutan, and 90% in India of water abstraction (World Bank 2013a).

³ Approximately 60% of India's agriculture is rainfed (Green et al. 2011; Government of India 2012).

production in 2005–2050, or about 3.9% annually (World Bank 2010a; Yu et al. 2010). Another study in Bangladesh found that a projected 27 cm sea-level rise by 2050, combined with storm surges, could inundate an area 88% larger than the area inundated by current storm surges (World Bank 2010a).

In Southeast Asia, a number of studies project a decrease in crop yields and, more specifically, in rice yields (Government of Viet Nam 2010; USAID 2013, Wassmann et al. 2009a; World Bank 2010b). In the Mekong River Delta, the rice yield is projected to decline by 6%–12%, while other crops will experience yield decreases of 3%–26% until 2050 in a wet (precipitation increases between 4%–20% across the country) and dry (precipitation decreases between 5%–16.5% across the country) version of the A1B emission scenario (World Bank 2010b). Studying different types of rice and wheat under 2.1°C, 1.8°C, and 1.6°C temperature increases above preindustrial levels in 2050 in Bangladesh, Yu et al. (2010) found that early-season rice, middle-season rice, and wheat yields are expected to increase, whereas late-season rice production might decrease as it reacts more significantly to changes in temperature rather than to changes in precipitation. Different modeling approaches are relatively consistent in terms of projecting a yield reduction in wheat production in the PRC of approximately 3% with a 1°C warming and of 8% in India (Liu et al. 2016; Lv et al. 2013; Kumar et al. 2014).

ADB contributed to this understanding of the potential impacts of climate change on agriculture in South Asia and Southeast Asia. In selected countries of South Asia, ADB (2014) reports the following results:

- **Bangladesh:** Not accounting for the potential impacts of CO₂ fertilization, overall rice could decline by approximately 17% and wheat production by 61% compared with a baseline situation.
- **Bhutan:** Rice yields could decrease by 6.7% (mid-altitude) and 12.6% (low altitude) by 2050.
- **India:** While rice yields could potentially increase in the northern states of India, rice yields may decline by 5.0% in the 2030s, 14.5% in the 2050s, and 17.0% in the 2080s in the southern states.
- **Sri Lanka:** Rice yields could decline by 3.6% to 19.8% by 2050 across seasons and climatic zones.

In selected countries of Southeast Asia (Indonesia, the Philippines, Thailand, and Viet Nam), ADB (2009) estimated that in the absence of any adaptation or technological improvements, rice yields could decline by up to 50% by 2100 (relative to 1990 levels). The study concluded that climate change will pose a serious threat to food security in the subregion.

In the PRC, ADB (2013a) concluded that crop yields may decline by 10% in drier scenarios. Wheat is the crop whose yield may be most impacted with declines ranging 8%–24% in 2050.

However, changing climatic conditions for crop growth are not the only pathway through which climate change impacts agriculture. Rising sea levels, flooding and increasing tropical cyclone intensity increase salinity and inundations and thus risks to rice production, especially in deltaic regions (Wassmann et al. 2009b).

The Mekong Delta, for example, an important rice production area, is threatened by sea-level rise due to its low elevation. A 30 cm sea-level rise by 2050 in the region may result in a loss of 193,000 hectares of rice paddies (about 4.7% of the Mekong River Delta provinces) due to inundation, and an even larger area of 294,000 hectares (about 7.2% of the same provinces) might become unsuitable for agriculture due to salinity intrusion (World Bank 2010b). Thus, rice production might decline by approximately 2.6 million tons per year (assuming 2010 rice productivity) representing a direct economic loss in export revenue of \$1.22 billion at 2011 prices (World Bank 2010b).

Future Changes in Land Productivity and Crop Yields in Central Asia

The five Central Asian countries (Kazakhstan, the Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan) are expected to be particularly vulnerable to climate change (Fay, Block and Ebinger 2010). Changing precipitation patterns, reduced runoff in the major river basins, and increasing temperatures will simultaneously put additional pressure on available water resources and increase agricultural water demand for rainfed and irrigated crops (Schlüter, Hirsch, and Pahl-Wostl 2010; Siegfried et al. 2012; Shah et al. 2013a, 2013b; Shah 2013a), thus increasing competition for water for agriculture, industry, and human consumption (Hanjra and Qureshi 2010). Reduced water

availability for irrigation is of key importance because of the high irrigation rates in the region (Sommer et al. 2013). However, climate change impacts on water resources are distinctly different for the next few decades compared to the end of the century. In the coming decades, meltwater is expected to increasingly contribute to river runoff which may lead to an increase in river runoff—however, simultaneously increasing evaporation rates may counterbalance this effect (Davletkeldiev et al. 2009). Thus, river runoff is expected either to remain unchanged or to increase slightly by 2030, even accounting for slightly higher precipitation rates. However, by the end of the 21st century, runoff generation rates in the mountainous areas of Central Asia may decline substantially (Government of Uzbekistan 2009).

Without accounting for changes in irrigation water availability, wheat yields in Central Asia might increase by 12% (ranging 4%–27%) across all periods and scenarios mostly due to higher winter and spring temperatures, less frost damage, and CO₂ fertilization (Sommer et al. 2013). However, heat stress in a 3°C world has been projected to affect wheat, maize, rice, and soybeans in 2071–2100 relative to the baseline period 1971–2000 in Central Asia, especially wheat production in Kazakhstan (Teixeira et al. 2013).

Both Kazakhstan and the Kyrgyz Republic are likely to suffer from drastic increases in desertification (covering up to 23%–49% of the Kyrgyz territory by 2100, in comparison to roughly 15% in 2000) (Shah et al. 2013a, 2013b). Without including adaptation measures and technological progress,

yields of almost all crops in Uzbekistan are expected to decrease by 20%–50% (in comparison to the 2000–2009 baseline) by 2050 in a 2°C world (Sutton, Srivastava, and Neumann 2013). Under a lower warming scenario of about 1.5°C warming, the declines are less pronounced or may even turn into yield increases of up to 13% in the eastern parts of the country. Alfalfa and grasslands may even benefit from a changing climate (Sutton, Srivastava, and Neumann 2013). However, including the effects of reduced water availability might lead to further stresses on yields. For example, by the 2050s, irrigation water demand might increase by up to 25%, while water availability could decline by up to 30%–40% (Sutton, Srivastava, and Neumann 2013). In some parts of Tajikistan, climate-induced water stress may decrease yields by up to 30% by 2100 (Shah 2013a). In Turkmenistan, climate change is likely to impact river runoff, reducing the runoff of the Amu Darya by 10%–15% and by 2%–5% in the Syr Darya River by 2050 and thus putting pressure on existing irrigation systems and crop production (Shah 2013b).

Future Changes in Land Productivity and Crop Yields in the Pacific

Numerous countries of the Pacific devote a large percentage of their land area to agricultural production. For example, that percentage reaches in excess of 60% in the Marshall Islands and Tuvalu and more than 40% in Kiribati and Tonga. With few, if any, options to expand agricultural areas, the projected impacts of climate change on agriculture are of particular concern. As shown in Table 3.1, these impacts could be severe.

Table 3.1: Relative Changes in Crop Yields under Climate Change in 2050 Relative to 2000 under the A1B Scenario in Selected Countries of the Pacific (Worse-Case Scenarios) (%)

	Papua New Guinea	Solomon Islands	Fiji
Cassava, rainfed	-30.8	-27.8	-36.5
Maize, irrigated	-3.2	-9.6	-6.1
Maize, rainfed	-3.8	-16.5	-7.0
Rice, irrigated	-8.3	-7.6	-7.1
Rice, rainfed	-7.5	-16.2	-11.0
Sugarcane, rainfed	-3.6	-12.9	-8.3
Sweet potato, rainfed	-10.9	-15.0	-13.4
Taro, rainfed	-13.0	-18.6	-17.5

Source: Adapted from ADB. 2013. *The Economics of Climate Change in the Pacific*. Manila.

Implications for Development and Food Security

Climate change poses significant threats to both agricultural production and food security in Asia and the Pacific. The available evidence for subregions or individual countries suggests that the biophysical impacts and agricultural production translate into substantial impacts on food security.

Around 7%–8% of the people living in Central Asia, mostly in rural areas, lack reliable access to food (Peyrouse 2013). Projected increases in population will aggravate climate change pressures on food security through impacts on agriculture and water availability (Lutz 2010). Moreover, large parts of household incomes are spent on food and many countries in the region are highly dependent on food imports (Meyers et al. 2012; Peyrouse 2013). For example, people in Tajikistan and in Uzbekistan spend 80% of their household incomes on food (Peyrouse 2013), and Tajikistan produces only 31% of the nation's food demand domestically. Therefore, rising international food prices are likely to strongly affect Central Asia (Meyers et al. 2012; Peyrouse 2013).

Additionally, per capita calorie availability could decrease by 7.6% in South Asia below 2000 levels (Nelson et al. 2010a). Consequently, it is projected that climate change could increase the number of malnourished children by 7 million compared to a no-climate-change scenario (Nelson et al. 2010a). Moreover, in the Indus, Ganges, and Brahmaputra river basins, reduced water availability for agricultural production may result in more than 63 million people no longer being able to meet their caloric demand with a temperature increase of 2°C–2.5°C compared to preindustrial levels by the 2050s (Immerzeel, van Beek, and Bierkens 2010).

Besides threatening food security, climate change impacts may also increase the need for food imports. In South Asia, for example, imports in 2050 may equal approximately 20% of production with 2°C warming by 2050, meaning import costs would increase to around \$15 billion per year compared \$2 billion per year in a no-climate-change scenario (Nelson et al. 2009).

Water Reservoir Systems and Agriculture

Historically, Asia has been the largest user of irrigation water by volume with surface water withdrawals for irrigation nearly tripling during the second half of the

20th century. The impacts of climate change on the level and variability in yields of important food crops will in many regions reflect the availability and reliability of water resources. Potential adaptation approaches to ease water scarcity in the region include integrated river basin management, widespread application of water-saving technologies (including smart irrigation techniques such as drip irrigation and soil moisture sensors), and water reuse. While climate change is anticipated to result in increased annual and seasonal precipitation over most regions of Asia, the extent to which this will translate into greater or more reliable water supplies for agriculture will in turn depend on the effective management of existing reservoirs and the construction of new storage.

Discharge of major Asian river systems is strongly seasonal, and reservoirs are required to smooth the annual discharge cycle, providing higher flows during the dry periods to ensure water supply for irrigation. More than 250 megadams and several tens of thousands of smaller dams were constructed along the main rivers of East Asia, South Asia and Southeast Asia. In the PRC alone, approximately 80,000 small and medium dams were built over the last decades (Gupta, Kao, and Dai 2012). Future construction of dams is also anticipated to take place mainly in the developing countries and emerging economies in Asia, with the Yangtze River likely to see the largest number of new dams (Zarfl et al. 2015).

Although Asia has experienced rapid expansion of dam and reservoir storage over recent decades, the existing storage remains low when compared to many advanced economies (Table 3.2), whether measured in terms of capacity per capita per year or in terms of the storage capacity as a fraction of total renewable water resources. Countries such as Bangladesh, India, Indonesia, Pakistan, and the Philippines exhibit low storage capacity, thus making them vulnerable to discharge variability.

While storage represents an important adaptation measure to global climatic and socioeconomic change, it is also challenged in a number of different ways. First, many reservoirs are characterized by large water losses due to seepage and surface evaporation. Evaporation is a critical factor particularly in hot and dry climates characterizing several Asian areas and must be taken into account when planning new dams as an adaptation to climate change. Increased temperature will lead to increasing evaporation

Table 3.2: Dam Storage, Storage per Capita, and Storage as a Percentage of Renewable Water Resources

Country	Total Dam Capacity (km ³)	Dam Capacity per Capita (m ³ /capita/year)	Dam Storage as a Fraction of Total Renewable Water Resources (%)
Bangladesh (2013)	6.5	40.2	0.5
PRC (2013)	829.8	589.6	29.2
India (2005)	224.0	189.9	11.7
Indonesia (2015)	23.0	89.4	1.1
Pakistan (2015)	27.8	147.2	11.3
Philippines (2006)	6.3	70.5	1.3
Australia (2015)	77.8	3,245.0	15.8
Canada (2015)	841.5	23,414.0	29.0
United States (2015)	735.9	2,278.0	24.0

PRC = People's Republic of China, km³ = cubic kilometer, m³ = cubic meter.

Notes: Year in parentheses is year for which dam storage data apply. 1 km³ = 1x10⁹ (1 billion) m³. Total renewable water resources are defined as the sum of total annual internal renewable water resources and annual net external renewable water resources, both inclusive of surface and groundwater (Margat, Frenken, and Faurès 2005).

Sources: Adapted from Food and Agriculture Organization of the United Nations (FAO). 2016. *AQUASTAT Main Database*. Rome; J. Margat, K. Frenken, and J.-M. Faurès. 2005. *Key Water Resources Statistics in AQUASTAT: FAO's Global Information System on Water and Agriculture*. International Work Session on Water Statistics. Vienna.

rates which must be factored into water balance accounting. Second, in addition to the potential adverse environmental effects of river regulation, the construction of reservoirs can introduce significant political issues when located on transboundary rivers, as is the case on many of the largest rivers in Asia. Third, resettlement and enforced migration of populations affected by construction of new dams and reservoirs (Biswas 2012) as well as the role of dams in sediment trapping (Gupta, Kao, and Dai 2012) are also important issues when considering new or expanded dam storage as an adaptation strategy. Each imposes additional social and environmental stress in the river basins.

Although water storage is of critical importance to the region, few studies have examined reservoir performance under projected climate change. Yang et al. (2016) investigated adaptive management strategies for a reservoir in the PRC and showed that it is possible to mitigate the adverse effects of climate change with an alternative reservoir management strategy. Similarly, Park et al. (2009) found that altering the reservoir management

strategy can help to adapt to projected changes in climate and preserve the water levels in two irrigation reservoirs used for paddy rice irrigation in the Republic of Korea.

While there are some databases, which collect information globally on the location and purpose of the dams and reservoirs (FAO 2016; Lehner et al. 2011), one of the major issues encountered in incorporating reservoirs into regional modelling frameworks is the lack of information on reservoir characteristics and operations history. Such information is not always shared between the riparian states along a river. It is essential to have information including reservoir topology and operations rules in major basins in order to understand climate change impacts, for example on hydropower production, flood risk management, water supply availability, and potential capacity for adaptation. Demand-side information is also required, including historical and projected trends in population and withdrawals for domestic and industrial water supply and irrigation.

Construction of new reservoirs and proper maintenance and adaptive management of existing facilities can

substantially increase adaptive capacity within Asia, both to projected climate and socially induced changes in water resources availability. There are also risks associated with reservoir construction and decisions on the construction of new reservoir storage must be taken on a case-by-case basis. It is also important not to view reservoirs as a panacea for increasing water stress, but rather to consider storage in conjunction with effective demand management, increasing water productivity in both irrigated and rain-fed agriculture, water reuse and a range of related interventions.

Changes in Land Productivity and Crop Yields: Future Research Directions

The implications of climate change impacts on development and food security are manifold. Unfortunately, consistent regional assessments that integrate biophysical impacts and their ramifications for development and food security are mostly lacking.

The review presented here shows that there are still a number of research needs to improve projections of climate change impacts on agricultural production and food security in Asia and the Pacific. These include the following:

- (i) The effects of increasing CO₂ concentrations on agricultural production are still uncertain. A better understanding of the interaction of rising temperatures, changing water availability, and CO₂ is crucial because positive CO₂ effects may absorb negative impacts of climatic changes (e.g., Challinor and Wheeler 2008).
- (ii) The effects of climate change on livestock are only poorly studied. While in general it seems that the direct effects of climate change on livestock, such as heat stress and reduced water availability, are likely to be negative, indirect effects may be positive such as in Uzbekistan, where the productivity of alfalfa and grasslands is expected to increase under warming conditions (Sutton et al. 2013).
- (iii) Even though a number of studies exist that couple biophysical impact modeling and socioeconomic assessments of climate change impacts, more integrated studies are needed to understand the full range of climate impacts in

terms of production changes, changes in trade patterns and so on, and the implications for regional development.

While there remains considerable uncertainty about the potential impacts of climate change on agriculture, a number of responses may be implemented and are likely to yield net positive benefits regardless of the actual (as opposed to projected) changes in climate conditions. Responses of this nature include

- (i) putting in place effective climate information systems, including early warning systems, to facilitate adequate responses by agricultural producers;
- (ii) promoting the dissemination of crop varieties which are climate (and especially heat) resilient;
- (iii) supporting investments in irrigation infrastructure, including water storage facilities where economic efficiency indicates such investment to deliver adequate rates of return regardless of future climate conditions; and
- (iv) exploring the possibility of putting in place risk-sharing instruments.

Marine Ecosystems

Southeast Asia's coral reefs are one of the richest centers of marine biodiversity globally. The Coral Triangle, a marine region spanning the tropical waters of Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands, and Timor-Leste, hosts around a third of the global coral stock and 76% of all known coral species (Hoegh-Guldberg et al. 2009). More than 100 million people living in the region's coastal area directly rely on its ecosystem services such as coastal protection and food security (Hoegh-Guldberg et al. 2009). Yet, almost 70% of the Coral Triangle's valuable reefs are currently at serious risk from destructive local forces such as overfishing, coastal development, and pollution (Hoegh-Guldberg et al. 2009). Climate change poses an increasingly serious threat to marine ecosystems, especially through the alarming effects of ocean acidification (Meissner, Lippmann, and Gupta 2012) and ocean warming (Lough 2012). The observed and projected changes of the Coral Triangle due to accelerating local and global stresses are associated with severe impacts for its marine life and coastal population.

Ocean Acidification

After having absorbed approximately half of all CO₂ emissions since the beginning of the industrial era, the world's oceans currently absorb approximately 26% of the annual anthropogenic CO₂ emissions from the atmosphere (Le Quere et al. 2012). The enhanced CO₂ uptake by the oceans causes distinct chemical changes of the seawater where an increase in dissolved CO₂ leads to a reduced availability of carbonate ions (Elderfield et al. 2005). Since the Industrial Revolution, global pH levels have decreased by 0.1 units while the concentration of carbonate ions declined by 25% (Hoegh-Guldberg 2014). Marine calcifiers such as corals and coralline algae, however, rely on carbonate ions to form and stabilize their calcium carbonate (CaCO₃) structures (Elderfield et al. 2005). Ocean acidification can thus result in reduced coral growth and coral skeleton weakening. The sensitivity of marine organisms to acidification was found to be enhanced by temperature increases and sea-level rise (Kroeker et al. 2013). Coral reef dissolution is estimated to set in at 560 parts per million (ppm) of atmospheric CO₂ concentration, which, according to the RCP8.5 (high emissions) scenario, will be reached by the mid-21st century (Silverman et al. 2009).

Ocean Warming

Besides the chemical stress of reduced pH levels in sea water, thermal stress also poses a serious threat to coral reef stability. Coral systems were found to be vulnerable to increases in sea surface temperature (SST) of 1°C–3°C (World Bank 2013b). SSTs above the tolerance range of coral reefs cause dieback of the symbiotic zooxanthellae algae (e.g., Goreau and Hayes 1994). The associated loss in color, energy, and nutrients supply eventually leads to coral bleaching (Goreau and Hayes 1994). This can produce severe damage to coral systems or even result in coral mortality. In general, bleaching is expected to occur if a region's warm season maximum temperature increases by more than 1°C for at least 4 weeks (Goreau and Hayes 1994). However, background climate conditions seem to influence the reef's sensitivity to temperature changes where regions with little natural temperature variability like the tropics show higher vulnerability to increasing SSTs (Carilli et al. 2012). Within the Coral Triangle, SSTs have increased by 0.09°C–0.12°C per decade between 1950 and 2008 and are projected to rise by 1°C–4°C (low and emissions scenario, respectively) toward the end of this century (Hoegh-Guldberg 2014).

Past and Projected Changes

The marine ecosystems of the Western Pacific region are highly responsive to chemical and physical changes of the ocean. Since 1980, regional coral cover has declined by about 50% with an average loss of around 1,500 km² per year (Bruno and Selig 2007). Projections clearly indicate that the combined effect of ocean warming and ocean acidification will negatively affect the growth, development, survival, calcification, and abundance of marine organisms throughout the 21st century (Kroeker et al. 2013). Under a high emissions scenario (4°C warming above preindustrial levels by 2100), all coral reef systems are projected to collapse due to mass coral bleaching (World Bank 2013b; Meissner, Lippmann, and Gupta 2012; Hoegh-Guldberg et al. 2009). Recent analyses show that even with a warming limited to 2°C (low emissions scenario), around 100% of coral reefs are projected to experience severe bleaching, resulting in massive coral dieback (Frieler et al. 2012). Under this scenario, coral communities are projected to decline to 10%–30% of their current abundance (Hoegh-Guldberg et al. 2009) with distinct consequences for the entire marine ecosystems (Meissner, Lippmann, and Gupta 2012). Still in a 1.5°C warming world, approximately 89% of coral reefs are expected to be subject to serious bleaching by 2100 (Frieler et al. 2012).

The Western Pacific coral reefs were identified as one of the most threatened marine ecosystems under future climate change (Meissner, Lippmann, and Gupta 2012). In 2030, bleaching events will likely start to occur on an annual basis under 1.5°C warming (World Bank 2013b). By 2050, the entire Coral Triangle is projected to be significantly affected by thermal stress (Meissner, Lippmann, and Gupta 2012). As a consequence, the Southeast Asian region is expected to experience severe coral loss and degradation. Other stresses such as coastal pollution and overexploitation will further enhance these processes. Within the Coral Triangle, the most vulnerable coral reefs are expected to be in the marine areas of the eastern Philippines (McLeod et al. 2010).

Socioeconomic Impacts

The Coral Triangle provides crucial ecosystem services to Southeast Asia's coastal communities. It serves as a vital source for food production, it is a fundament of the region's tourism sector, and it provides coastal protection from storm surges and sea-level rise (World Bank 2013b). The total potential annual economic net benefit per

square kilometer of healthy coral reef in Southeast Asian countries is estimated between \$23,100 and \$270,000 (Burke, Selig, and Spalding 2002). Its stability thus plays a critical role in the livelihood and economic welfare of the region's coastal population.

The projected degradation and loss of coral reefs will likely be associated with reduced species richness and species extinction, threatening the ecosystem's biodiversity (World Bank 2013b). Such ecosystem changes can have severe impacts on food security by negatively affecting local fisheries (Elderfield et al. 2005). In Southeast Asia, reef fish and seafood cover more than 35% of the coastal population's dietary animal protein demand (Burke et al. 2011). Under a number of emissions scenarios, the Coral Triangle's food provision capacity for coastal communities is projected to be halved by 2050 (Hoegh-Guldberg et al. 2009). The cumulative loss in value of reef-related fisheries in Southeast Asia for 2000–2050 is estimated at around \$57.98 billion under the business-as-usual scenario with an increasing annual loss rate of \$6 billion in 2050 (Brander and Eppink 2015). The expected biodiversity loss of marine ecosystems can further pose serious risks to the tourism industry by diminishing the region's appeal as a tourist destination (World Bank 2013b). As an increasingly important share of the Coral Triangle countries' GDP comes from tourism revenues, this can significantly threaten the countries' economic welfare (Hoegh-Guldberg et al. 2009).

Policy Implications

The region's strong socioeconomic dependence on its marine ecosystems clearly highlights the urgent need for adjusted national conservation policies to preserve coral reefs and the ecosystem services they provide (Burke, Selig, and Spalding 2002). These should include stringent ocean governance to reduce and prevent overfishing, as well as integrated ecosystem-based coastal zone management in order to reduce local stresses and increase the resilience of coral systems (Hoegh-Guldberg et al. 2009; Hilmi et al. 2015). Respective policies need to recognize the strong coupling between conservation and development. Moreover, the implementation of local knowledge will be essential to develop fruitful adaptation

strategies for affected communities (Hoegh-Guldberg et al. 2009). Overall, the extreme vulnerability of coral reefs to a warming level of 2°C highlights the importance of fast decarbonization and the significance of the 1.5°C temperature boundary for coastal economies.

3.2 Climate Change and Human Health

Over the last decades, the Asia and Pacific region has seen strong improvements in the health status of its population (United Nations 2015). Climate change now poses a significant risk to human health, threatening to reverse much of the progress that has been achieved. Even if strong mitigation actions are taken globally, adaptation measures will be needed in the coming decades to buffer at least some of the significant effects on human health to be expected (Watts et al. 2015).

This chapter presents Asia-specific results on climate impacts in the 2030s and 2050s for selected climate-sensitive health outcomes, taken from a recent quantitative impact assessment of the World Health Organization (WHO 2014). It also provides selected examples of recent disease epidemics and health occurrences in Asia that can be related to climatic factors, in particular extreme weather events (Box 3.1). These examples highlight the climate sensitivity of Asian societies in terms of human health impacts.

The Effects of Climate Change on Selected Causes of Deaths in Asia and the Pacific

The causal links between climate change and human health are particularly complex, integrating a myriad of physical, biological, and socioeconomic factors (McMichael, Woodruff, and Hales 2006). Therefore, quantitative models currently exist only for a few of the outcomes that will determine the overall burden of climate change on human health. WHO recently provided one of the few consistent quantitative risk assessments (WHO 2014), investigating climate impacts on diarrheal diseases and stunting in children, on heat-related mortality in the elderly, and on vector-borne diseases (malaria and dengue fever).⁴

⁴ WHO (2014) also includes estimates on mortality from coastal flooding. These are discussed elsewhere in this report.

Box 3.1: Pakistan Floods of 2010 and Diarrheal Diseases

In August 2010, Pakistan experienced record-breaking floods inundating an area the size of England, affecting 20 million people and causing 1,800 direct fatalities (Warrach, Zaidi, and Patel 2011). Countless cases of infectious diseases were reported in the affected areas in the weeks and months following the floods. Among these, diarrheal diseases were the most prominent (Baqir et al. 2012), especially among children (Warrach, Zaidi, and Patel 2011). The importance of diarrheal diseases in the aftermath of natural disasters, often being the leading cause of deaths, has been generally recognized (Kouadio et al. 2012). Given the increasing risk of severe flooding under climate change in many Asian countries (Hirabayashi et al. 2013), improved quantitative models of climate impacts on human health are urgently needed to take into account the effects of extreme events on diarrhea and other infectious diseases.

Sources: H. Warrach, A. K. M. Zaidi, and K. Patel. 2011. Floods in Pakistan: A Public Health Crisis. *Bulletin of the World Health Organization*. 89(3). pp. 236–237; M. Baqir et al. 2012. Infectious Diseases in the Aftermath of Monsoon Flooding in Pakistan. *Asian Pacific Journal of Tropical Biomedicine*. 2(1). pp. 76–79; I. K. Kouadio et al. 2012. Infectious Diseases Following Natural Disasters: Prevention and Control Measures. *Expert Review of Anti-Infective Therapy*. 10. pp. 95–104; Y. Hirabayashi et al. 2013. Global Flood Risk under Climate Change. *Nature Climate Change*. 3(9). pp. 816–821.

These estimates take into account demographic and socioeconomic development and related changes in the basic health status of the affected populations. The climate data used correspond to a medium–high emissions scenario run through five different global climate model versions. These project a global mean temperature rise of approximately 1.1°C (range: 0.9°C–1.4°C) in the 2030s and approximately 1.7°C (range: 1.5 °C–2°C) in the 2050s above the baseline climate of 1961–1990, with more or less pronounced changes in the different regions. In addition to climate uncertainty, most of the health impact models employed in the assessment also account for uncertainty in parameters and other model specifications of represented processes. Maximum impact estimates can be considered as “worst cases” for the purpose of adaptation planning.

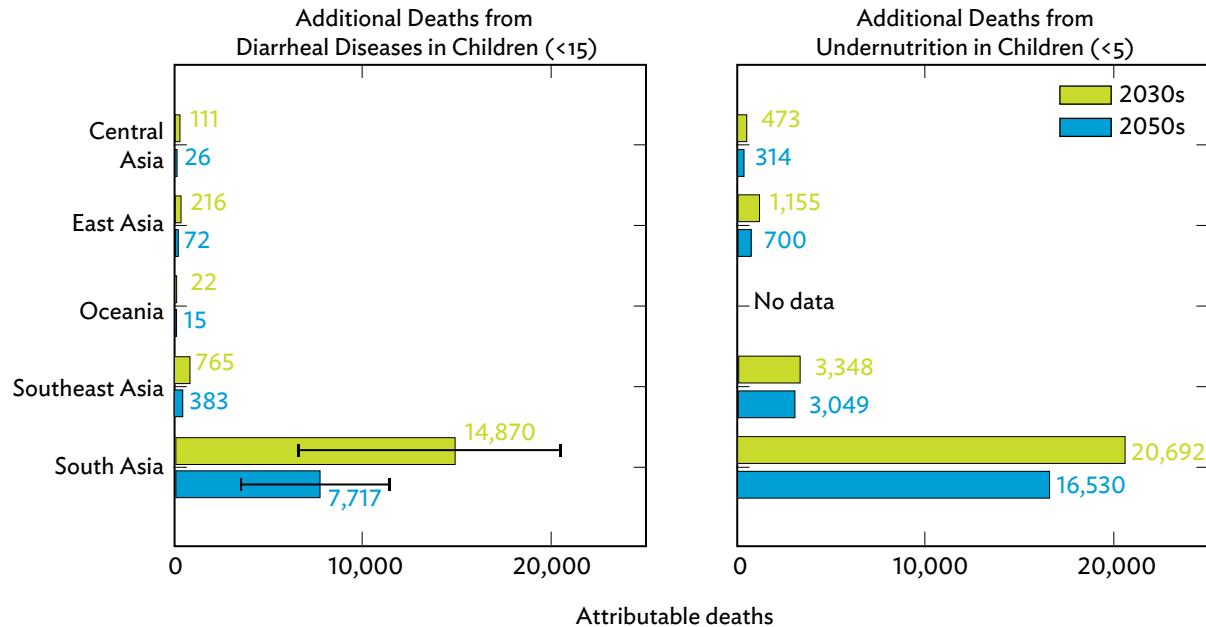
Diarrheal Diseases and Undernutrition in Children

Diarrhea remains one of the leading direct causes of child mortality worldwide (Liu et al. 2014), only surpassed by pneumonia. At the same time, undernutrition is one of the major underlying risk factors for mortality in small children, with about 45% of global deaths in small children (<5 years) ultimately attributed to undernutrition in 2011 (Black et al. 2013). Socioeconomic development (including access to safe water and sanitation, food availability, and education) essentially determines the prevalence of these conditions. In particular, children in poor households may be particularly more vulnerable to the impacts of climate change as they often experience weaker health status.

While the relationship between precipitation, water availability, and diarrheal disease is highly complex (Lloyd, Kovats, and Armstrong 2007), there is a clear and established link between ambient temperature and diarrheal disease occurrence in children (Checkley et al. 2000), encompassing many different enteropathogens causing the disease. Most quantitative work on climate impacts, including the WHO assessment, has so far considered stunting (defined as inadequate height for age) as one of the major manifestations of undernutrition (Lloyd, Kovats, and Chalabi 2011). Climate change will mainly affect child stunting through its strong effects on crop yields, which are expected to decline, especially in low latitudes including many Asian countries.

Taking these relationships into account, the WHO models project that by the 2030s climate change will cause up to 350 *additional* child deaths (<15 years) due to diarrheal disease per year in Central Asia, East Asia, and Oceania; up to 800 in Southeast Asia; and approximately 15,000 in South Asia (Figure 3.1). The additional death burden in very small children (<5 years) due to climate change effects on undernutrition is estimated to be considerably higher, with between approximately 500 attributable child deaths (in Central Asia) and 20,000 (in South Asia) in the 2030s in this age group alone (Figure 3.1). For both health outcomes, expected impacts for the 2050s follow the same tendencies as for the 2030s, but are smaller because of the assumed strong improvements in general health conditions in the considered regions. Generally,

Figure 3.1: Estimated Future Annual Additional Deaths of Children Attributable to Climate Change



Source: Adapted from World Health Organization (WHO). 2014. *Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s*. Geneva.

estimates are highest for South Asia, because of its large population but also because of its strong vulnerability to climate change.

By comparison, ADB (2014) estimated the number of cases of diarrhea across all ages to increase significantly under a higher emissions scenario in selected countries of South Asia (Table 3.3).

While climate change effects on mortality are without doubt the worst outcome from the perspective of the individual, morbidity and often described lifelong impacts of diarrheal diseases and undernutrition during childhood (Victora et al. 2008) also put large burdens on societies and would therefore need to be considered in a more comprehensive impact assessment. Further research is required to improve the currently available models for these health outcomes. Future work on diarrheal diseases will also need to account for water availability. Global undernutrition models need to be developed further to take into consideration other manifestations

of undernutrition such as deficiencies in minerals and vitamins (USGCRP 2016).

Heat-Related Mortality in the Elderly (>65 Years)

Humans living in different geographical locations are adapted to their local climate through a number of behavioral and physiological mechanisms (McMichael, Woodruff, and Hales 2006). Accordingly, the “comfort temperature”, defined as the temperature where mortality rates are observed to be at their minimum, varies strongly across the globe. At the same time, there is ubiquitous evidence that mortality rates increase as the temperature rises above the site-specific comfort value, in temperate as well as in tropical regions (Gasparrini et al. 2015). These increases in heat-related mortality are especially apparent during heat waves when temperatures are particularly high for a number of consecutive days (Box 3.2). Mortality attributed to heat is above all related to cardiovascular and respiratory disorders (McMichael, Woodruff, and Hales 2006). Elderly people, especially those living in poverty

Table 3.3: Projected Annual Morbidity and Mortality from Diarrhea by Selected Country (All Ages) under a High Emissions Scenario

	2030	2050	2090
Bangladesh			
Morbidity	4,089,000	5,841,660	13,668,560
Mortality	3,828	7,031	21,708
Bhutan			
Morbidity	209	439	1,658
Mortality	0	0	0
India			
Morbidity	25,565,370	42,424,470	116,150,404
Mortality	1,408	3,155	8,032
Maldives			
Morbidity	26,467	69,290	200,850
Mortality	4	12	41
Nepal			
Morbidity	213,614	366,853	1,158,430
Mortality	77	191	467
Sri Lanka			
Morbidity	234,498	498,054	1,308,944
Mortality	27	56	156

Source: Adapted from ADB. 2014. *Assessing the Costs of Climate Change and Adaptation in South Asia*. Manila.

and in poor housing quality, are known to be particularly vulnerable (Vardoulakis et al. 2014).

Assessments of the effects of climate change on heat-related mortality usually rely on statistical relationships established based on daily time series of temperature and mortality rates. These models need to take into account delayed effects, such as the well-described phenomenon (called “harvesting”) of a drop in daily mortality rates a few days after a heat wave, because the pool of susceptible individuals has been depleted (Gasparrini and Armstrong 2010). Models such as the one applied by WHO mostly assume that the basic form of the established statistical relationships will be constant in the future. However, acclimatization to generally higher temperatures in the future is at least partly included by raising the comfort temperature inherent in the model (Honda et al. 2014).

Under the assumption of moderate acclimatization, the WHO model estimates that by the 2030s the expected increase in the number of warm and/or hot days across Asia will cause between 1,000 and almost 10,000 deaths annually in the >65 years age group across

the different Asian regions (excluding Oceania where projected numbers of attributable deaths are less than 20; Figure 3.2). For the 2050s, these numbers are considerably higher, given the higher increase of regional temperatures as climate change proceeds further into the century along with underlying assumptions on aging populations (see WHO 2014).

Adaptation measures, taken both at the level of individual citizens and governments (such as installing air conditioning, greening urban spaces, and establishing early warning systems and heat emergency plans) have the potential to significantly bring down the number of heat-related deaths compared to business as usual (McMichael, Woodruff, and Hales 2006). Further research is necessary to better account for these different adaptation options and their limitations when modeling climate change effects on heat-related mortality. In particular, special attention should be paid to better understanding the needs of the poor as the impacts of climate change on health are known to be unequally distributed across income classes. Last but not least, a more comprehensive assessment of climate change impacts on human health

Box 3.2: Heat Wave 2015 in India

In May 2015, India experienced the worst heat wave in a decade with five consecutive days over 43°C in New Delhi, and ambient temperatures reaching as high as 48°C in other southeastern cities (Di Liberto 2016). More than 2,300 people died due to heatstroke and dehydration, according to Indian news sources (NDTV 2015). So far, no scientific assessment of the full health burden of this heat wave has been made, but it is important to note that estimates of heat excess deaths will almost certainly be much higher. This is because calculations of heat-related mortality also take into account deaths caused *indirectly* by high temperatures, which are often delayed by a few days, in addition to the usually much smaller number of immediate deaths due to conditions *directly* related to extreme heat and sun exposure (Gasparrini and Armstrong 2012). The Indian heat wave of 2015 is also an interesting case for further scientific research because it points to possible limits of adaptation. Power outages across the country shut off the desperately needed air conditioning in many locations, leaving an even greater number of people exposed to extreme temperatures (The Guardian 2015). Failure of actions taken will therefore need to be accounted for in scientific assessments of adaptation options.

Sources: T. Di Liberto. 2016. India Heat Wave Kills Thousands. *Climate Watch*. pp. 9–13; NDTV. 2015. Heatwave Toll Crosses 2300, Andhra Pradesh Reports over 1700 Deaths. 2 June; A. Gasparrini and B. Armstrong. 2012. The Impact of Heat Waves on Mortality. *Epidemiology*. 22(1). pp. 68–73; *The Guardian*. 2015. India Heatwave Kills More Than 500 People. 25 May.

also needs to consider mortality related to cold. It is well established that temperatures below the local optimum are associated with increases in mortality, even in tropical regions (Gasparrini et al. 2015). However, there is still large uncertainty as to whether climate change will bring about a significant reduction in cold-related mortality as one of the few expected benefits from climate change (Ebi and Mills 2013; Kinney et al. 2015).

Vector-borne Diseases: Malaria and Dengue

The number of malaria incidences has dropped significantly in many Asian countries, but it remains a major health challenge for the region (United Nations 2015). Dengue has dramatically grown over recent decades and is now the leading cause of hospitalization and death among children in many Asian countries (WHO 2016).

The decisive role of economic development, including strong improvements of health services and infrastructure, for the endemicity of malaria is well established (Gething et al. 2010). However, the seasonality of its transmission has also long been recognized and has been attributed to climatic factors (Gubler et al. 2001). Temperature is known to determine development rates of the insect vector of malaria and to influence vector reproduction and survival, human–vector contact, and biting rates (Caminade et al. 2014). For dengue, the important role of climatic factors has equally been shown (Hales et al. 2002). Besides climate, the recent spread of dengue

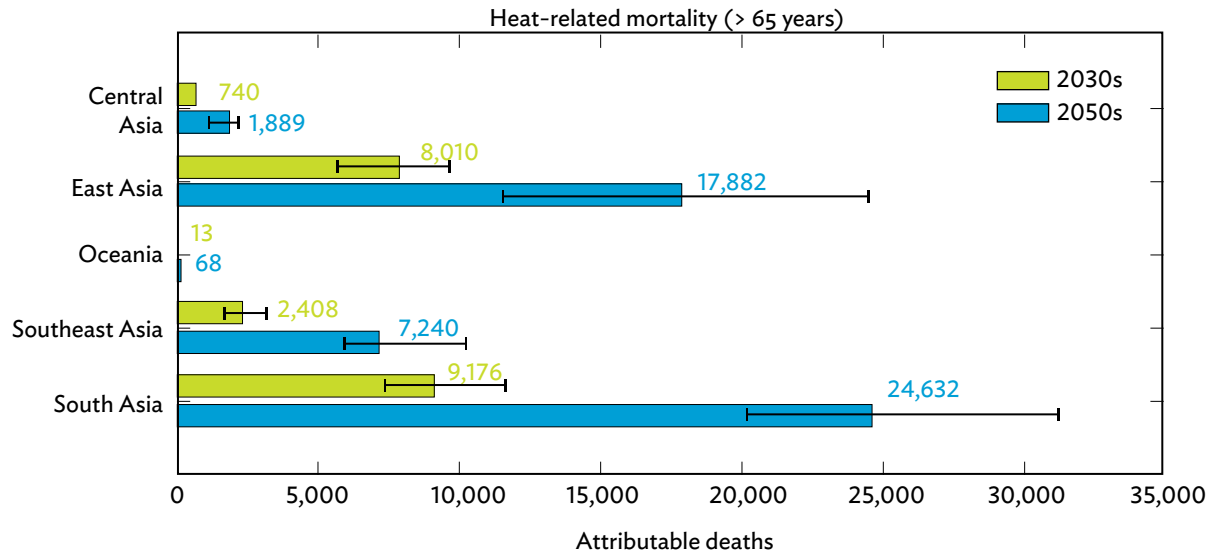
appears to be dependent on rapid urbanization rates and expanding global transport networks (Bhatt et al. 2013).

Based on a statistical model for the geographical distribution of malaria, WHO projects that by the 2030s, up to 50 additional malaria-related deaths in Oceania, up to 500 Southeast Asia, and up to 2,000 in South Asia will be attributable to climate change (Figure 3.3). By the 2050s, this number rises to almost 10,000 attributable deaths per year in South Asia. According to the dengue model applied, by the 2030s, climate change will cause approximately 30 additional deaths related to dengue per year in East Asia and approximately 200 additional deaths in South Asia.

ADB (2014) also studied the possible impacts of climate change on malaria and dengue (Table 3.4).

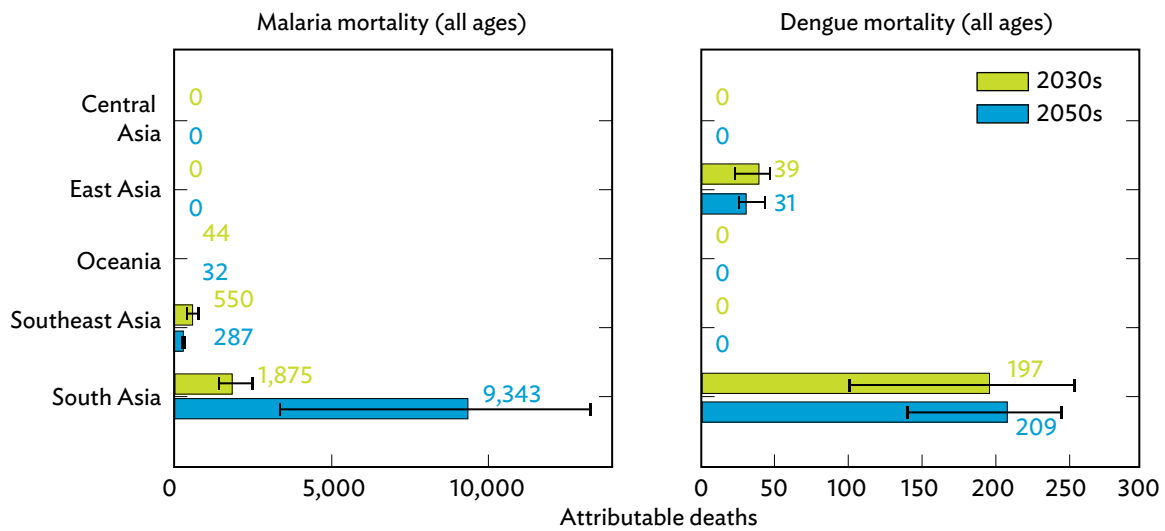
The presented results have to be interpreted with caution because they rely on estimated changes in the population at risk due to shifts of the geographic disease distributions and *current* national mortality estimates. Changes in year-to-year transmission variability, population epidemiology, and extreme events are not taken into account (Box 3.3). Estimates are also highly dependent on the assumption of sustained GDP growth across the Asian region (WHO 2014), an assumption that has recently been called into question by a recent study that projects the impact of climate change on national GDP (Burke, Hsiang, and Miguel

Figure 3.2: Estimated Future Annual Additional Deaths of Elderly Attributable to Climate Change



Source: Adapted from World Health Organization (WHO). 2014. *Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s*. Geneva.

Figure 3.3: Estimated Future Annual Additional Deaths Attributable to Climate Change



Source: Adapted from World Health Organization (WHO). 2014. *Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s*. Geneva.

Table 3.4: Predicted Annual Morbidity and Mortality from Dengue and Malaria by Selected Country under a High Emissions Scenario

	Dengue			Malaria		
	2030	2050	2090	2030	2050	2090
Bangladesh						
Morbidity	4,807	9,158	47,100	147,102	209,443	440,194
Mortality	133	227	619	855	1,116	2,525
Bhutan						
Morbidity	8,735	17,621	63,996	48,205	75,679	222,892
Mortality	126	220	565	84	135	400
India						
Morbidity	34,408	59,443	172,425	369,570	2,994,122	3,465,181
Mortality	287	483	1,458	6,554	16,371	45,830
Maldives						
Morbidity	5,836	10,546	34,539	49	79	229
Mortality	49	94	324	0	0	0
Nepal						
Morbidity	67	135	394	42,862	61,346	147,049
Mortality	0	0	0	33	117	1,772
Sri Lanka						
Morbidity	61,081	115,000	353,727	9,381	19,694	99,329
Mortality	324	670	2,033	331	586	1,721

Source: Adapted from ADB. 2014. *Assessing the Costs of Climate Change and Adaptation in South Asia*. Manila.

2015). In addition, future work needs to account better for large uncertainties in current models of malaria and dengue. The first multimodel estimates of climate change impacts on malaria have recently been presented (Caminade et al. 2014). These could be built upon to improve the results for the Asia and Pacific region shown here.

In Indonesia, the Philippines, Thailand, and Viet Nam, an estimated 24,632 people died from malaria and dengue in 1990. With global warming, deaths are expected to increase by 18% in 2020 (ADB 2009).

Conclusions and Future Research Directions

The health impact estimates presented highlight that climate change poses a significant risk to the health and well-being of the population of Asia and the Pacific, especially of the most vulnerable—the very young and elderly. However, it is important to take into consideration that many important diseases sensitive to climate change (e.g., waterborne diseases such as cholera and schistosomiasis, asthma, and other respiratory syndromes

from air pollution and airborne allergens) and the effects of extreme events have been omitted from the analysis (ADB 2011). The overall burden from climate change to be expected in the different Asian regions by the 2030s and 2050s is therefore projected to be much greater than reflected by the mortality estimates shown here.

Specific recommendations for the improvement of some of the existing quantitative health models have been provided. Enhancing short-range and long-range forecasting and warning systems and improving surveillance are key among numerous other no-regret options.

Overall, future research will need to strive for a more comprehensive understanding of climate impacts on human health. In fact, all of the biogeophysical impacts discussed in this report will have important repercussions on human health. New models and quantitative approaches are needed to translate more of the existing impact estimates on the biogeophysical level into standardized measures of human health and well-being.

Box 3.3: Large Outbreaks of Dengue in 2015/16 in South Asia and Southeast Asia

In much of South Asia and Southeast Asia, a sharp increase in dengue cases occurred in 2015. The Philippines, for example, reported more than 169,000 cases, representing almost a 60% increase in case numbers compared to the previous year (WHO 2016). Large outbreaks have also been reported for Malaysia, Thailand, and Viet Nam (Outbreak News Today 2015). Recent research suggests that this development could at least partly be related to the strong El Niño phenomenon of 2015/16. Based on time series data for 1993–2010 covering eight Southeast Asian countries, the scientists revealed clear relationships between temperatures as related to El Niño and incidence rates of dengue (van Panhuis et al. 2015). Since global climate variability and extreme events are so far not represented in most dengue models, recent events indicate that current estimates could decisively underestimate the true climate impacts on the disease.

Sources: World Health Organization (WHO). 2016. *Dengue and Severe Dengue*. <http://www.who.int/mediacentre/factsheets/fs117/en/>; OutbreakNewsToday. 2015. *Asia Dengue Fever Update: Vietnam, Thailand and Malaysia*. 15 June; W. G. van Panhuis et al. 2015. Region-wide Synchrony and Traveling Waves of Dengue across Eight Countries in Southeast Asia. *Proceedings of the National Academy of Sciences*. 112(42). pp. 13069–13074.

3.3 Climate Change and Urban Areas

As indicated in Part 1 of this report, an increasing percentage of the population of Asia and the Pacific lives in urbanized areas. This percentage increased from approximately 18% in 1950 to an estimated 48% in 2014 and is expected to reach 64% by 2060 (UN DESA 2014). In 2014, Asia accommodated 16 of the 28 megacities of the world (with more than 10 million inhabitants) and 28 of 44 large cities (with 5 million–10 million inhabitants). By 2030, Asia is anticipated to host eight more megacities, four of which in India (Chennai, Bangalore, Hyderabad, and Ahmadabad).

The potential impacts of climate change on cities, and more generally on urban areas, have been subject to numerous analyses (Hallegatte, Henriot, and Corfee-Morlot 2010; McEvoy 2007; Roaf, Crichton, and Nicol 2005; Wilby 2007). As a result of poverty, unplanned informal settlements, and insufficient infrastructure, cities in developing Asia and the Pacific—many of which are located in coastal areas and floodplains of the region—are even more vulnerable to the impacts of climate change (Aerts and Botzen 2014; Suskind 2010).

This subsection on climate change and urban areas focuses on two important emerging issues: heat burden in cities, and exposure to sea-level rise and storm surges.

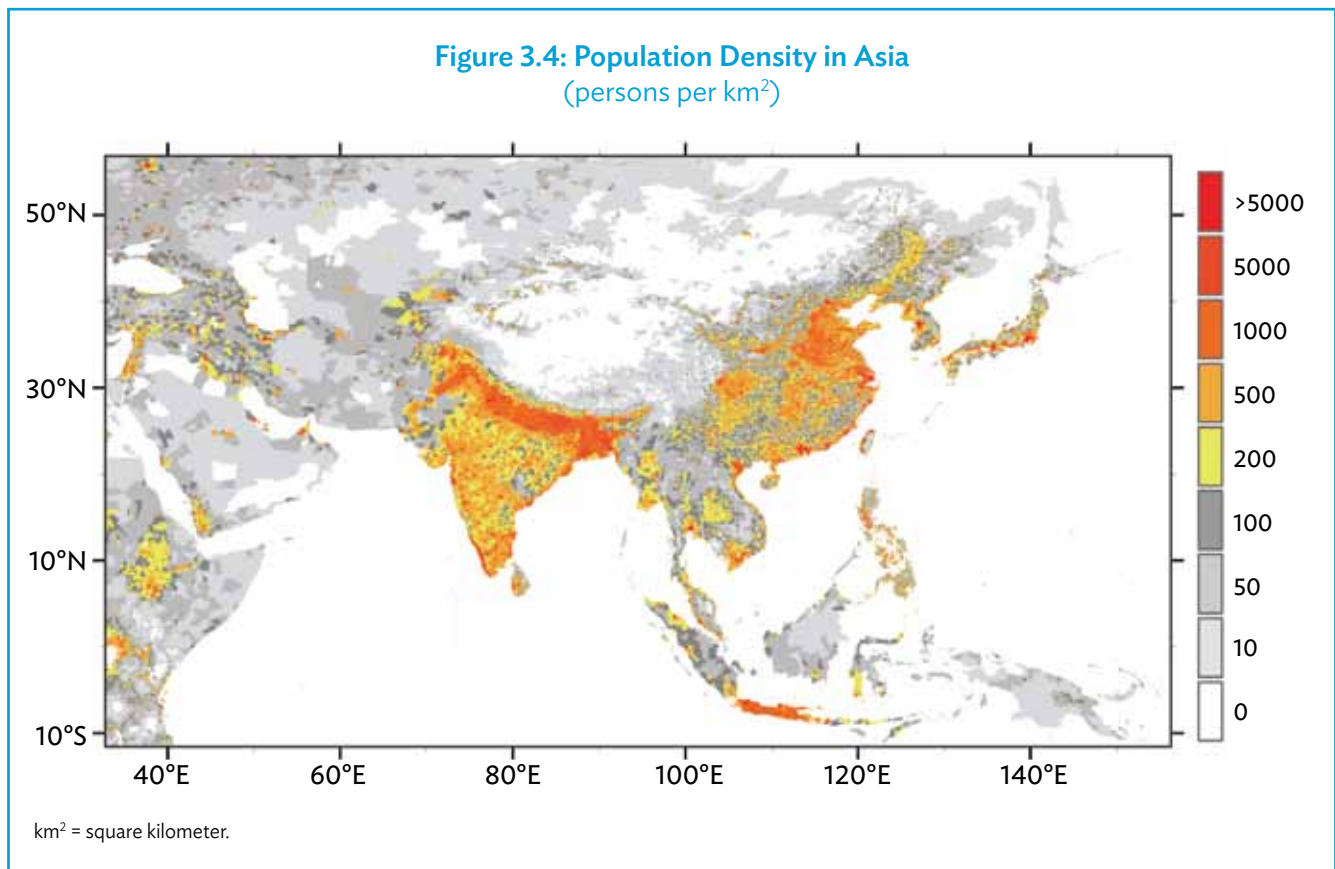
Heat Burden in Cities

Rapid urbanization is usually characterized by an increased share of sealed and artificial surfaces which, coupled

with increased population density (Figure 3.4), private transportation, and usage of air conditioners for space cooling, leads to an increase in waste heat in urban areas, often referred to as the urban heat island (UHI) effect.

The city-specific level of human heat tolerance among urban populations has been investigated by studies that relate elevated ambient temperature or heat to mortality records of a city (Baccini et al. 2008; Ballester et al. 2011; Chung et al. 2015; Gasparrini et al. 2015). However, this information is very local, often provided in incomparable temperature metrics and determined by varying parameters. Moreover, it requires exact mortality records, which are often not homogeneously given. A simple method to approximate the urban populations' present and future heat tolerance levels is needed to better estimate their resilience toward heat and meet the challenges that this will bring along for urban and health-care planning. This method should be able to overcome the very local nature of the city-specific threshold temperatures that denote the heat tolerance levels and simultaneously the onset of mortality among an urban population. Data other than the often unreliable mortality records (e.g., environmental data such as climatic and morphological data) should be employed to establish this method. This method will help to increase the data density for urban heat tolerance levels in Southeast Asia.

Soaring urban temperatures have not only resulted in excess mortality, but also led to a deterioration of ambient air quality by favoring formation of various air pollutants and their precursors such as tropospheric ozone and



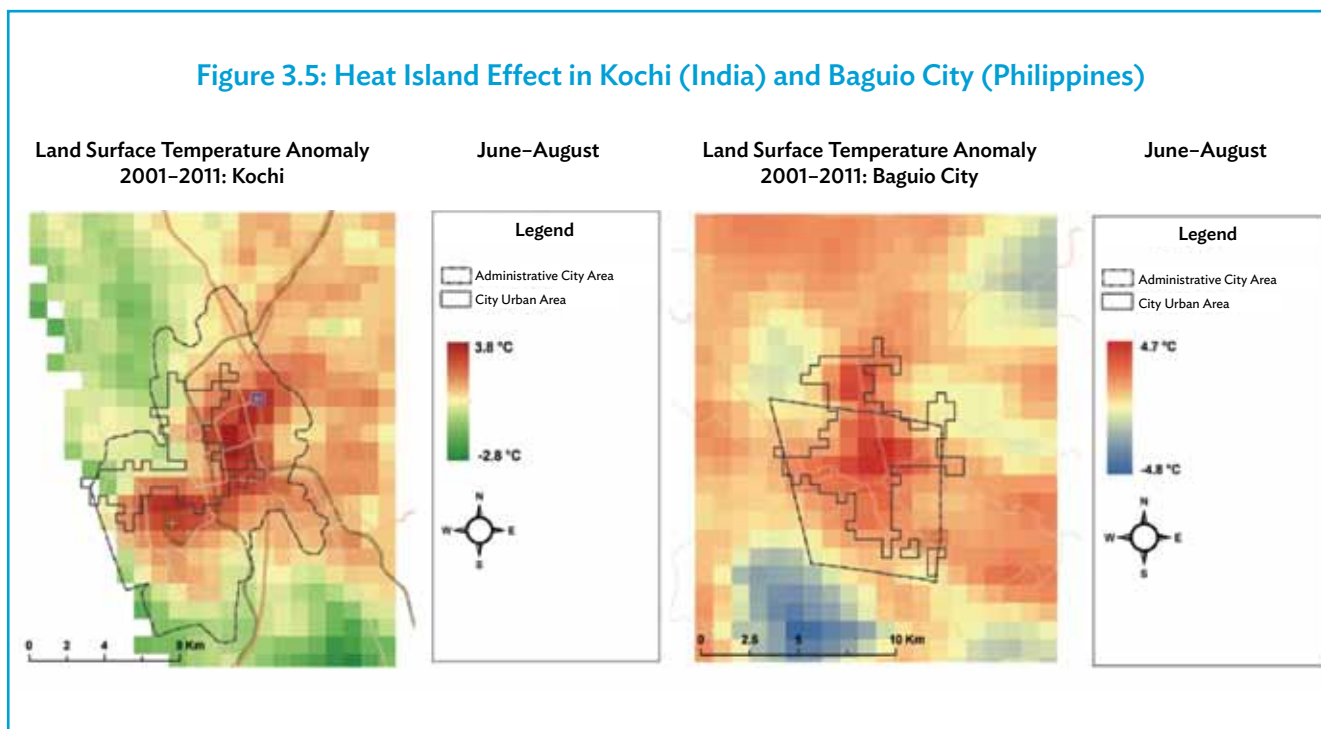
nitrogen oxide (Sarrat et al. 2006). These pollutants put people at additional risk of respiratory disease and other health problems. In addition, higher temperatures in cities lead to increased electricity demand for air conditioning. The waste heat generated therefrom, in turn, amplifies the heat stress. It is therefore reasonable to expect that measures aiming to mitigate the UHI effect will bring about a range of cobenefits, among others, improved air quality and decreased mortality.

In Asian countries, UHI studies are mainly conducted in cities where long-term data records are available. There is an abundance of studies for cities in the PRC: Beijing (Liu et al. 2007; Miao et al. 2009; Yang et al. 2016), Shanghai (Cui and Shi 2012; Tran et al. 2006), Wuhan (Ren et al. 2007). Similarly, for cities in Japan: Tokyo (Ashie and Kono 2011; Kataoka et al. 2009) and Osaka (Masumoto 2006). However, for rapidly urbanizing and populating countries, such as India and the Philippines, there is still a lack of research on the increasing thermal burdens (examples from the Philippines and India are shown in

Figure 3.5). Kataoka et al. (2009) analyzed the long-term trends in surface temperature in several large Asian cities (including Bangkok, Jakarta, Manila, Osaka, Seoul, and Tokyo) for estimating the effects of urban warming. These selected cities exhibit an increase of UHI intensity by 0.6°C to 2°C during the 20th century, whereas the global mean temperature has only increased by 0.7°C over the same period.

Kim and Baik (2004) investigated the characteristics of the daily maximum UHI intensity in the six largest cities of the Republic of Korea (Busan, Daegu, Daejeon, Gwangju, Incheon, and Seoul) during the period 1973–2001. The average annual daily maximum UHI intensity in all cities tends to increase with time. However, it tends to be smaller in coastal cities (Busan and Incheon) than in inland cities (Daegu, Daejeon and Gwangju), implying the possible cooling effect of sea breeze. A UHI study by Tran et al. (2006) based on remotely sensed surface skin temperature for eight Asian megacities (Bangkok, Beijing, Ho Chi Minh City, Manila, Pyongyang, Seoul, Shanghai, and

Figure 3.5: Heat Island Effect in Kochi (India) and Baguio City (Philippines)



Tokyo) shows that all selected cities experience significant surface UHIs in summer or in the dry season, with the highest UHI up to 12°C in Tokyo. The intensity and extent of UHIs are found positively correlated to population size of the cities, indicating the significant impacts of urbanization on the development of UHIs in Asia. A recently published literature review by Santamouris (2015) investigated the UHI studies conducted in the Asian region. It found that the cities in Asia exhibit significant UHIs and that the UHI intensity is the most pronounced in temperate climate zones (Figure 3.6).

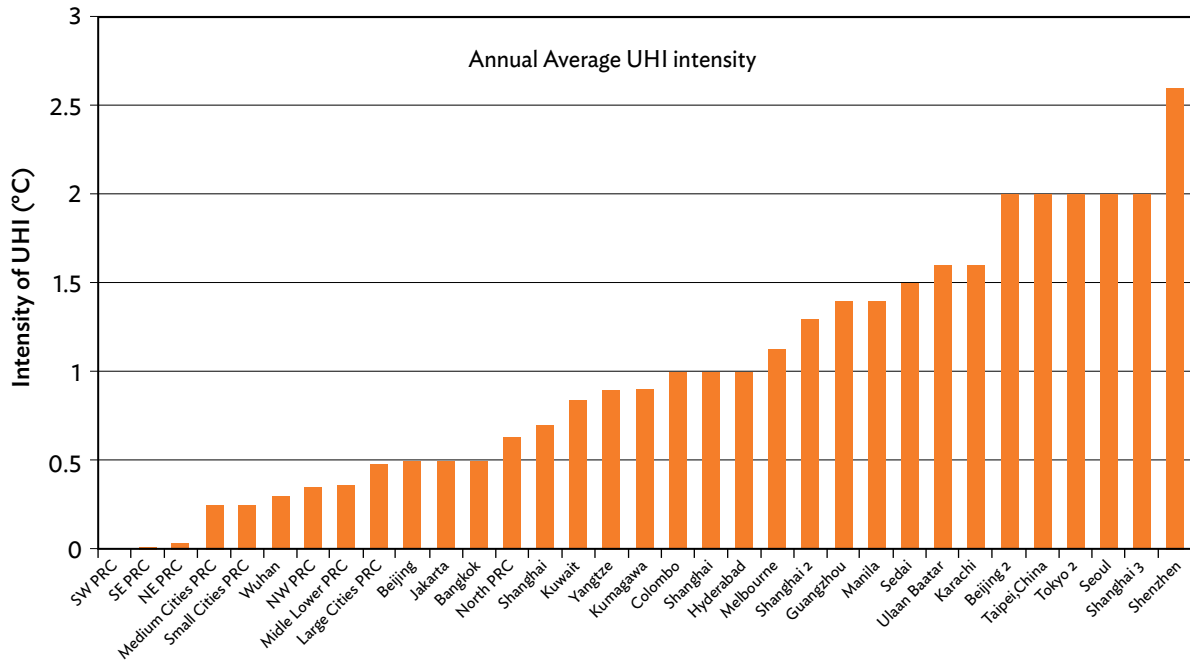
Apart from these results, a systematic study investigating heat load on an urban level and considering different climate change and urban growth scenarios is lacking. Such an examination is mandatory for an assessment of further effects, for example, health effects related to UHI effects. Such an assessment is even more urgent considering that recent empirical estimates show that the global mean air temperature is nonlinearly related to heat stress. In other words, the same future warming as realized to date could trigger larger increases in human heat stress and associated health impacts than historically experienced (Matthews, Wilby, and Murphy 2017).

Damages of Sea-Level Rise in Cities

Sea-level rise has differed markedly across the region over the last 2 decades, ranging from 2–3 millimeters per year (mm/year) in the Andaman Sea up to 9–10 mm/year in the Molukka Strait (Strassburg et al. 2015). The foreseeable intensification of coastal floods due to SLR constitutes a serious threat to many regions in proximity to the oceans. A considerable amount of research has been devoted to the assessment of SLR impacts as well as potential response strategies to attenuate the negative consequences. The threat is exacerbated by the fact that coastal regions are centers of attraction for population and economic activity (McGranahan, Balk, and Anderson 2007). Consequently, there is no doubt that the societal impacts from SLR are most striking in light of their economic relevance as they represent threats to commerce, business, and livelihood (Dossou and Glehouenou-Dossou 2007). Accordingly, most studies on SLR impacts focus on the economic and/or monetary aspects with the objective of quantifying the costs of SLR for a given region.

Contrary to existing standards on coastal protection (CPSL 2010), a methodological standard on the assessment of the potential impacts from SLR is missing. In general,

Figure 3.6: Urban Heat Island Intensity in Selected Cities of Asia and the Pacific



NE = northeast, NW = northwest, PRC = People's Republic of China, SE = southeast, SW = southwest, UHI = urban heat island.

Source: M. Santamouris, M. 2015. Analyzing the Heat Island Magnitude and Characteristics in One Hundred Asian and Australian Cities and Regions. *Science of the Total Environment*. 512–513. pp. 582–598.

adequate impact assessments require the consideration of environmental as well as anthropogenic aspects and thus involve contributions from diverse research fields. Nevertheless, albeit in differing implementations, the following two components of assessing SLR impacts can be found in most studies:

- (i) Projections of mean sea levels and their dependence on global temperatures represent an indispensable basis for meaningful investigations of SLR impacts (Milne, Long, and Bassett 2005; Church and White 2011). In contrast to the global mean sea level, floods are local events. Accordingly, their consequences and their intensification induced by SLR need to be assessed on corresponding scales from first principles. Due to the fact that extreme floods are induced by the coincidental occurrence of several factors, they cannot be predicted in the long term and are thus characterized by

stochastic means (Mudersbach and Jensen 2010). Nevertheless, the mean sea level is of particular importance as it constitutes the base quantity on which surge effects are superimposed (Orlic and Pasarić 2013) and is widely acknowledged to be the most relevant driver for future sea level extremes

- (ii) The consequences of individual flood events are typically inferred from a flood damage function (Merz et al. 2010) which relates the magnitude of a flood with the resulting damage costs. As a damage function is always based on “what if?” considerations and provides the damage costs for a presupposed flood event, a meaningful characterization of flood threats requires the integration of damage functions with the stochastic of flood occurrences. By doing this, the expected annual flood damage can be deduced and represents the most widespread measure for flood risk.

Technically, the damage estimation for individual flood events is typically based on relative damage functions—damage functions that provide the fraction of damaged assets in the considered area. In order to obtain absolute damage values, these fractions are multiplied by the total exposed asset value. As the exposed values directly scale the resulting damage, their estimation is crucial. Two approaches are prevailing:

- (i) Employing the widely-used assumption from the insurance industry that a population's assets are proportional to its GDP, the spatial distribution of assets is often deduced from population density data. This approach has been followed, for example, by the Dynamic and Interactive Vulnerability Assessment (DIVA) model (Hallegatte et al. 2013; Hinkel et al. 2014).
- (ii) As proposed by the Joint Research Centre (JRC) (Huizinga 2007), the estimation of exposed assets can be based on land cover and use data, which is ultimately scaled by an economic indicator in order to reflect regional differences in price levels.

Due to a scarcity of empirical data, none of the two approaches has been proven to be superior. In general, SLR impact assessments are clearly distinct by their scale of analysis: global or regional coverage, or local case studies. Due to their scale of analysis, the two approaches differ drastically in their level of detail, accuracy, coverage, and set of decision makers or stakeholders. On the one hand, the most prominent reports—e.g., by the IPCC (Wong et al. 2013), the United Nations Framework Convention on Climate Change (Nicholls 2007), or the World Bank (Nicholls et al. 2010)—all refer exclusively to the same two large-scale assessment models, namely DIVA (Hinkel and Klein 2009) and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) (Tol 2002). While the DIVA model is based on the consideration of coastal segments of similar characteristics and assesses multiple SLR impacts and protection measures, FUND is a more general, economic model.

The advantage of large-scale assessments is their spatial coverage of continents to global which allows for impact comparisons between regions. Their disadvantage is the coarse level of detail, the limited accuracy, and the fact that cities—the cores of human and economic activities—are not represented explicitly.

On the other hand, there are a vast number of case studies investigating SLR impacts on the local scale (for an overview, refer to Hunt and Watkiss 2011). The advantage of case study analyses is the high level of detail and resulting high accuracy; many publications do explicitly treat cities (Aerts et al. 2014). Since such case study analyses of cities imply considerable efforts and data requirements, they cannot easily be compared or transferred from one city to another one. Moreover, different authors use different methodologies. As a consequence, it is not feasible to simply upscale analysis of case study cities by aggregation.

Accordingly, there is a gap between large-scale and case study assessments. To our knowledge, SLR impacts on cities have never been investigated for a complete set of cities in a given area—in a comparable and transferable manner, covering an extended region of continental scale. Therefore, it is important to do so, because recent studies show that the expected damage in cities will rise with a larger pace than SLR itself (Boettle, Rybski, and Kropp 2016). Further, given the large regional difference in sea-level trends, such an approach will be essential. Nevertheless, approaches capable of considering the special configuration of cities (beyond a high population density) are lacking. Considering recent trends and projections of urbanization, the relevance of cities will become even more pressing in the future (Barragán and de Andrés 2015; Jiang and O'Neill 2017). This holds in particular for Southeast Asia, where the flood protection standards are less developed (compared to Europe) and high urbanization rates can be found (Murakami et al. 2005). At the same time, detailed impact assessments are rare for this region.

Considering the potential risks emerging from sea level rise, the question of possible response strategies arises naturally—particularly in view of increasing rates of sea level rise (Obeysekera and Park 2013). Even without further warming, the global mean sea level will continue to rise in the forthcoming decades due to an inexorable melting of land ice and the thermal expansion of the oceans. Society is therefore bound to face the consequences and adaptation is urgently needed as a complement to greenhouse gas mitigation (Nicholls 2007). Commonly discussed and implemented adaptation measures comprise the construction or reinforcement of hard protection (i.e., engineered constructions such as dikes or sea walls), soft protection (e.g., beach nourishment or wetland creation), as well as land-use and urban planning

(Delcan Corporation 2012). Assessing the effectiveness of these measures is mostly limited to dikes and sea walls which are commonly assumed to avert any damage from flood events up to a given defense level (see, e.g., the DIVA model or Hallegatte et al. [2013]). In contrast, soft protection measures and land-use planning are less straightforward to assess in a quantitative way and hence remain largely disregarded in literature, particularly on larger scales. However, their effectiveness has been investigated in several small-scale studies (Primavera, Rollon, and Samson 2011; Sano et al. 2015).

From an economic point of view, flood defense measures can entail enormous costs. The World Bank, for instance, estimates the costs for dike construction and/or upgrade and beach nourishment by the 2040s to be in the \$26 billion–\$89 billion per year range (Nicholls and Cazenave 2010). Whether such implementations are beneficial or not is commonly examined by means of a cost–benefit analysis, which compares all monetary flows related to a given measure (Costa, Tekken, and Kropp 2009; Gamper, Thoni, and Weck-Hannemann 2006). In any case, when different protection strategies are compared, a set of options to be investigated must be chosen in the first place. Although this preselection is arguably of high relevance for policy making, surprisingly little attention is paid to it in the literature. While, on the local scale, well-elaborated strategies can be found (Aerts et al. 2014), the suggested protection measures on larger scales are often very vague and not always well chosen. The DIVA model, for example, supposes dike constructions of a given protection height along the entire considered coastline, independent from the prevailing land use and sometimes ignoring existing river courses (Hinkel and Klein 2009).

Consequently, in line with the absence of cities in large-scale assessments, a meaningful, spatially explicit representation of protection is also lacking. There is no automatized, systematic, and detailed analysis of potential dike constructions, corresponding costs, and avoided damage.

Standardized Damage Assessment: Future Research Directions

Assessments of impacts from SLR are either based on case studies or are aggregated on much larger scales. Although Hunt and Watkiss (2011) report that climate risks most frequently addressed in existing studies are associated with SLR, health, and water resources, only a small number

of cities, mostly in countries of the OECD, have derived quantitative estimates of the costs of climate change risks under alternative scenarios. Flood exposure is apparently increasing in coastal cities due to growing populations and assets, SLR, and subsidence (Hallegatte et al. 2013). Studying the 136 largest coastal cities, the authors estimate that the average global flood losses in 2005 are approximately \$6 billion per year and will increase to \$52 billion by 2050. Of the top 20 cities with the largest increase of annual losses between 2005 and 2050, 13 are located in Asia: Guangzhou (PRC), Mumbai (India), Kolkata (India), Shenzhen (PRC), Tianjin (PRC), Ho Chi Minh City (Viet Nam), Jakarta (Indonesia), Chennai–Madras (India), Surat (India), Zhanjiang (PRC), Bangkok (Thailand), Xiamen (PRC), and Nagoya (Japan). This illustrates the strong exposure of Asian cities. However, in terms of the urban areas affected by a 1 m SLR, Viet Nam is the only Asian country among the top 10 most impacted countries (Dasgupta et al. 2009).

In summary, South Asia and Southeast Asia are particularly vulnerable to flooding since there is a concentration of low-lying populated deltas (Nicholls et al. 2010). Although ongoing research is performed in regard to this topic, systematic, more precise (in terms of expectable damage, adaptation costs, and spatial resolution), and comparable analyses are still lacking as indicated by the literature review.

3.4 Climate Change and Security

Major political and military institutions have acknowledged the significance of climate change as a conflict threat multiplier, especially in already unstable regions (Brzoska and Fröhlich 2015; Brzoska and Oels 2012; US Department of Defense 2015; UNDP 2011; UN General Assembly 2009). However, uncertainties regarding the climate change–conflict nexus remain as it remains difficult to isolate single variables and adequately assess their effect on the formation of conflicts (Buhaug et al. 2014).

Climate effects and conflicts in the historic and prehistoric past have been addressed by a substantial body of literature (Cullen et al. 2000; Drysdale et al. 2006; Kennett et al. 2012), in which Asia is also well represented (Donges et al. 2015; Zhang et al. 2007). For example, Zhang et al. (2007) use paleoclimatic data to explore the effects of cooling

phases on the occurrence of warfare and population decline in preindustrial PRC. Several studies have shown evidence that the frequency of war and the breakdown of previously stable societies are closely interwoven with changes in climate conditions (Cullen et al. 2000; Donges et al. 2015).

There is an ongoing academic debate over the question whether environmental factors contribute significantly to the rise of conflict, or whether political, social, and economic factors dominate (Clark 2007; Raleigh and Urdal 2007; Reuveny 2007). Scholars reject the simplistic view of a monocausal link between changes in the climate and conflict occurrence as too reductionist and largely unverifiable, due to the complex interplay of socioeconomic and environmental factors (Wischnath and Buhaug 2014). However, there is strong evidence that changes in the climate have influenced the occurrence of conflicts in the past.

Economic, societal, and ethnic friction can be exacerbated by external disturbances such as climate change. Schleussner et al. (2016) use a statistical approach to analyze the coincidence rate of armed conflict outbreaks and climate-related natural disasters, which proves to be exceptionally high in ethnically fractionalized societies. Their results indicate that interaction between ethnic fractionalization and climate-related disasters enhances the probability of violent conflict outbreak. Being ethnically divided, already conflict-affected, as well as particularly vulnerable to climate change, the authors suggest that Central Asia is a high-risk region for future violent conflicts.

Energy resources, natural resources, and poverty are significant variables in the generation of conflict constellations. Their vulnerability to climate change impacts is likely to be a future driver of instabilities. Each of these will be discussed.

Energy Supply

Enabling access to stable and abundant energy resources will continue to be an important issue for policy makers in Asia (ADB 2010). However, as discussed in Part 1 of this report, climate change impacts on energy supply cover a broad array of issues from decreasing water availability for the purpose of hydropower generation and for the cooling of thermal power plants, to demolished grid infrastructure due to extreme events and coastal SLR.

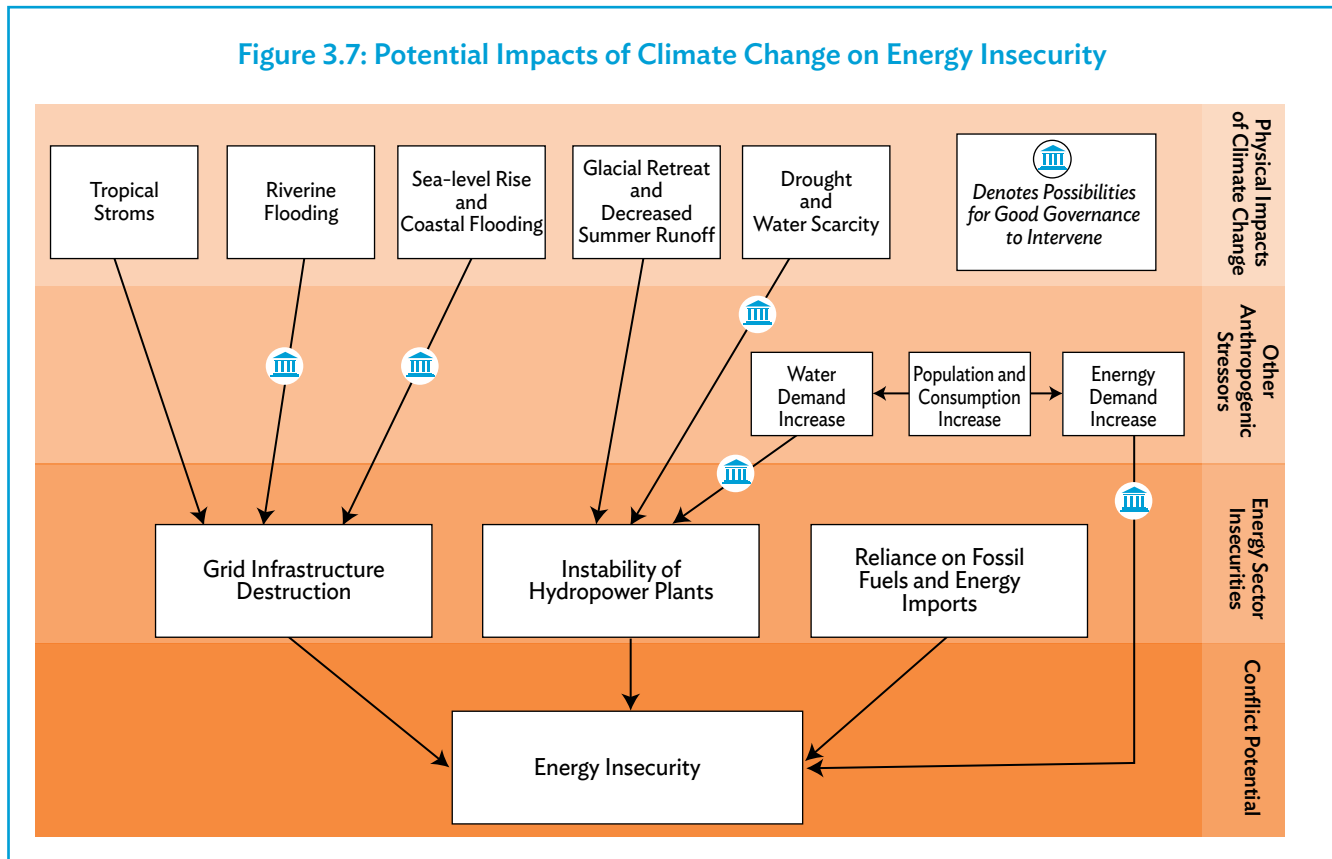
As shown in Figure 3.7, energy supply risks in the hydropower sector arise from the combination of higher water demand and a decline in water availability due to droughts and glacial melt (Dai 2011; Immerzeel, van Beek, and Bierkens 2010; Miyan 2015; Vivekananda 2011; Zhao, Ding, and Moore 2014). SLR can have destructive effects on grid infrastructure in coastal urban areas (Brown, Hanson, and Nicholls 2013; Satterthwaite et al. 2007). In Asia, SLR may especially challenge energy infrastructure development in coastal cities of numerous countries including Bangladesh (Rahman and Rahman 2015) and India (Garg, Naswa, and Shukla 2015), while flood risks in the highly urbanized Pearl River Delta in the PRC specifically threaten big cities such as Hong Kong, China; Macau, China; Shenzhen; and Guangzhou (Yang et al. 2014).

Potential future supply risks for fossil fuel-reliant economies will add to existing challenges of societies and cities if transformations toward sustainability are not undertaken (Chapman 2014; Kerschner et al. 2013). In fact, many Asian countries (e.g., India) and megacities face the danger of being locked into dependence on high-carbon technologies and costly energy imports (Mat et al. 2014; Sovacool 2014; Vivekananda 2011). Furthermore, investments in fossil fuel production, such as coal-fired power plants, could turn into stranded assets as renewable energy sources achieve market dominance. On the contrary, a study on the energy security of the PRC shows that through mitigation efforts the PRC was able to bolster national energy security (Wu et al. 2012).

Considering the impacts of climate change on energy supply, the traditional view on energy security based on nationally securing and protecting fossil fuel resources is outdated. It should be replaced with a medium to long-term model that takes into account the planetary boundaries, as well as local environmental effects on human safety, such as air pollution. Such a paradigm would aim at independently providing stable energy access by drawing on renewable resources, over which conflicts would likely not arise.

The energy supply insecurity resulting from the factors discussed above could, in turn, create or exacerbate (violent) conflict and threaten national security. This is especially the case where poor governance fails at realizing mitigation and international cooperation opportunities (Herberg 2004).

Figure 3.7: Potential Impacts of Climate Change on Energy Insecurity



In order to limit the effects of climate change on energy supplies and potential consequent conflicts, the Asia and Pacific region may benefit from putting in place a number of preventative mechanisms aimed at reducing the potential for conflicts associated with securing access to energy supply. These may include the following: (i) more intensified and integrated regional collaboration to improve projections and offsetting of power shortages, (ii) the accelerated development of sustainable and off-grid energy resources in order to enhance energy autonomy, and (iii) investing in climate-resilient supply networks (Ebinger 2011; Scheffran 2015; Vivekananda 2011).

Resource Scarcity and Water Insecurity

Climate change will increasingly undermine human security by reducing access to vitally important natural resources (Barnett and Adger 2007). Most scientific literature regarding resource conflicts in Asia agrees that existing social conflicts will be aggravated by the biophysical impacts of climate change and their interference with human livelihoods (Giese and Sehring 2007; Vivekananda

2011). Such effects include impacts on the hydrological cycle through rising temperatures and prolonged droughts, SLR and salinization of soils, as well as changes in water runoff patterns (Turrall, Burke, and Faurès 2011). Intrastate conflicts (e.g., between single Indian federal states over water access; Carius, Tänzler, and Winterstein 2006) and interstate-conflicts (e.g., in the regions of the Indus and the Ganges–Brahmaputra–Meghna river basins; Uprety and Salman 2011) could worsen under future climate change. A higher occurrence of water stress in regions reliant on glacial meltwater and transnational freshwater resources may thus contribute to the potential of conflicts.

Central Asia is projected to be affected by declining water availability for irrigation during summer, caused by changing seasonal runoff availability due to earlier snowmelt (Siegfried et al. 2012). Glacial melting will have a negative impact on food production in this already arid region (Lioubimtseva and Henebry 2009; WBGU 2007). Because Central Asia has experienced political instability, social inequality, and ethnic fractionalization (Schleussner

et al. 2016; WBGU 2007) and because water is the most conflict-related resource in the region (Perelet 2007), future conflict intensification could occur, particularly in the Fergana valley (Bernauer and Siegfried 2012; Siegfried et al. 2012), the Aral Sea region (WBGU 2007), and the Kura–Araks region (Carius, Tänzler, and Winterstein 2006). In combination with population growth and lagging economic development, agrarian societies are therefore highly vulnerable to the effects of climate change (Raleigh and Urdal 2007). Moreover, climate change-related threats to food security in Central Asia could reduce livelihood options in the agriculture sector and thus potentially trigger migration movements within the region or abroad (see also the following section on poverty) (World Bank 2014).

In South Asia, societies are likely to face aggravated water and food insecurity related to increasing droughts (Miyani 2015) and the destabilization of the Himalayan water tower (Scheffran 2014) which currently supplies water to 1.3 billion people living in the basins of the great Asian rivers (Blondel 2012), as discussed in Part 2 of this report. The Brahmaputra and Indus river basins would be the most affected by the changes in the Himalayan hydrological system (Immerzeel, van Beek, and Bierkens 2010; Vivekananda 2011). In this region, India and Bangladesh are not only geographically highly exposed to climate change impacts, but also have large low-income populations dependent on agriculture with limited adaptive capacities (Vivekananda et al. 2014). Furthermore, the diversion of water upstream in the basin could aggravate the situation if no effective transboundary river management is implemented (Blondel 2012).

As South Asia is extremely vulnerable to climate change, projected impacts on crop productivity could strongly influence the region's food prices and supply (Bandara and Cai 2014). As a consequence, future population displacement and conflict could be heightened (Butler 2009). However, social instability due to food insecurity is not only caused by physical changes. It can also be aggravated or induced by poor governance. Chatterjee et al. (2016) note that half of the Asian population will be living in cities by 2020, creating a higher food demand in Asian cities and simultaneously fostering an urbanization of peripheral agricultural plots. Therefore, Asian cities are expected to increasingly depend on national and global supply chains and be exposed to food security threats from both localized and distant disaster events.

In order to enable the sustainable development of food production and thus reduce conflict potential, Butler (2009) calls for a radical transformation, including in environmental, agricultural, and demographic governance; changes in consumption; and a reduction of inequality. Chatterjee et al. (2016) emphasize the necessity to strengthen the supply chain and improve the capacity for food storage in order to reduce food insecurity and thus improve the resilience of cities. To avoid future resource-based conflicts, Blondel (2012) proposes a cooperative, regional, multilateral resource management initiative. Such a joint approach would help realize mitigation and adaptation policies. Community-based resource management would increase the adaptive capacity by building networks that help in coping with natural disasters and by preserving the resilience of the regional resources and ecosystems (Tompkins and Adger 2004).

At a national level, the negotiation of further water-sharing treaties and other cross-border agreements, especially for the Brahmaputra basin and with PRC, might help to avoid destabilization (Adams and Adger 2013). Moreover, the scientific literature reflects that collaborative resource management over shared international freshwater resources is of utmost significance to ensure sustainable water supplies and avoid future threats to human security related to water scarcity (Cooley et al. 2009; David and Pandya 2009; Draper and Kundell 2007). However, the implementation of effective transboundary water management poses significant challenges, since it necessitates the complex coordination of divergent institutional settings, resources, and management practices of the respective countries (Timmerman et al. 2011). Especially in South Asia, the management of water resources has become more complex, owing to the region's high vulnerability to climate change (Adams and Adger 2013).

Poverty

Climate change not only threatens energy, water, and food security, but also has the potential to generate friction by destabilizing economies. The discussed vulnerabilities in energy supply, agriculture, and access to water in the face of climate change effectively threaten the livelihoods of millions of people (Scheffran 2014). Resource scarcity, the loss of crop yields, and damaged infrastructure are likely to affect most those who are already socially deprived (Bandara and Cai 2014). Schmidhuber and Tubiello (2007) point out that the socioeconomic environments

in which impacts occur may be more defining for the severity of the effects on populations than the climate impacts themselves. This of course applies only within a certain corridor of magnitude of the climate impact. The IPCC assessment shows that the potential for adaptation decreases for the majority of climatic risks in a 4°C world (IPCC 2014). Overall, the poor have very limited resources to adapt to changes in their environment and often work in the agriculture sector, making them most vulnerable to the impacts of climate change, despite having contributed least to it (Huq and Reid 2007; Schmidhuber and Tubiello 2007).

Vivekananda (2011) and Blondel (2012) both view poverty combined with dependence on natural resources as critical factors for the occurrence of violent conflict. Scheffran (2015) and Beisheim (2013) assess the connection between poverty, food prices, and conflict. Due to the increasing global resource competition for energy production, large amounts of water and land are no longer available for food production, which in turn has already had negative consequences on global food prices, thus adversely affecting the poor (Beisheim 2013; Scheffran 2015).

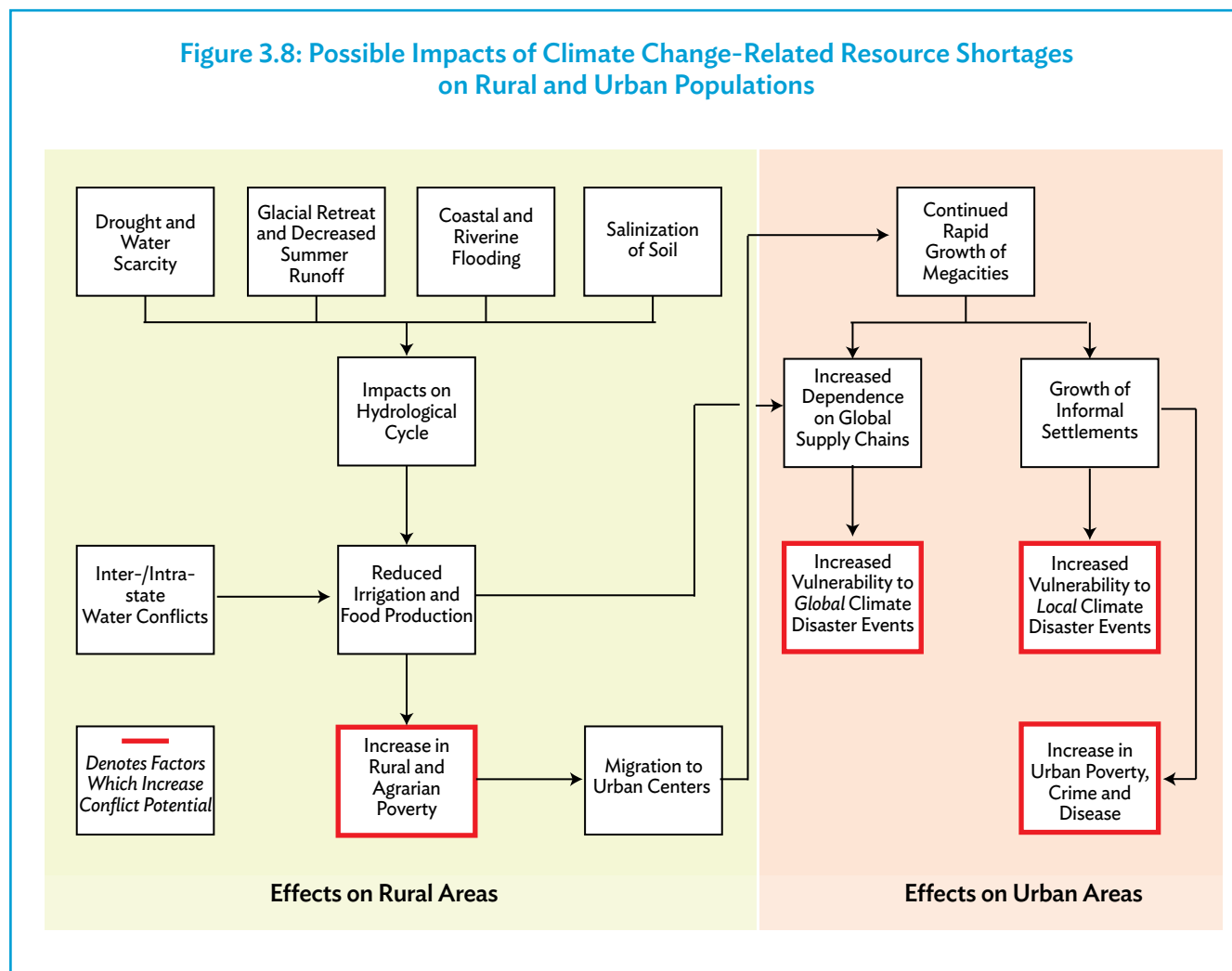
Climate change will affect the rural and the urban poor differently. A study on the nexus of droughts and conflict in Asia and Africa found that droughts increase the likelihood of conflicts for groups which are dependent on agriculture and those who are politically marginalized in countries with high poverty levels (Uexkull et al. 2016). People whose livelihoods depend on agriculture will be immediately affected by changes in the natural environment. For example, the vulnerability of farmers in Punjab province of Pakistan to climate-related risks was aggravated by already existing constraints on available freshwater, access to income, and a fragile infrastructure (Abid et al. 2016). Their capacity for adaption is impaired by a lack of knowledge as well as by resource scarcity (Abid et al. 2015). Another example of the effects of climate change on agricultural livelihoods in Asia is the rural exodus in the PRC, which already poses great governance challenges and could further increase due to aggravated climate impacts (WBGU 2007). Comparable adverse effects on the rural population might become even more relevant for agrarian societies with strong socioeconomic disparities (Blondel

2012) such as those found in Kazakhstan, Uzbekistan, and Turkmenistan (WBGU 2007). Therefore, existing socioeconomic tensions between impoverished groups might be enhanced (Giese and Sehring 2007).

The climate impacts on urban poverty and the resulting potential of societal friction and conflict also require further assessment. For instance, Crank and Jacoby (2015) analyze the nexus of urban poverty, violence, and climate change using a macrosocial approach.

Increasingly, a large zone of peripheral settlements, where mostly poor migrants live, has been surrounding the core city. Those informal settlements lack basic services such as health care or infrastructure and are exposed to various levels of crime. In such hazard-prone locations, slum dwellers are highly vulnerable to the impacts of climate change owing to weak governance and a barely climate-resilient infrastructure (Dodman and Satterthwaite 2008). Clark (2007) notes that a less adaptable infrastructure in poorer countries highly increases the probability of conflict. Crank and Jacoby (2015) conclude that in areas where governance is weak and poverty is high, groups of organized crime may be able to recruit new members easily. High prevalence of organized crime may further weaken the influence of government agencies, increase violence, and cause societal friction or conflict. Vivekananda (2011) also points to the issue of weak governance in his analysis on how climate change adds to urban poverty and therefore gives rise to instabilities in Karachi, Pakistan. The megacity has experienced rapid population growth, whereas basic infrastructure has not been adequately expanded. Therefore, the urban poor are affected by disease, poor water supply, a lack of sanitation, as well as food and physical insecurity. Vivekananda argues that climate change impacts of rising sea levels, combined with the city's social geography, will increase social disorder and political instability by putting further pressure on the impoverished population. A similar conflict constellation has been addressed in a case study by Saha (2012), who took a qualitative approach in analyzing how past flooding events have contributed to the occurrence of gun violence between slum dwellers in Dhaka. Nevertheless, further substantial qualitative and quantitative research regarding the nexus of urban poverty, climate change, and violence could provide more elaborated and far-reaching insights.

Figure 3.8: Possible Impacts of Climate Change-Related Resource Shortages on Rural and Urban Populations



In addition to the issues raised earlier, pro-poor adaptation policies are often constrained by the fact that urban adaptation planning and the strengthening of urban governance are often not included or emphasized in national climate change adaptation policies and thus do not receive adequate funding and support. Furthermore, nongovernment organizations that promote community-based disaster risk reduction are largely not supported by local governments, nor is their knowledge integrated into decision-making processes (Ahammad 2011).

To alleviate poverty, the building of inclusive green economies is a key factor with multiple benefits. For instance, a study by Abid et al. (2016) highlights the necessity to address the current obstacles to adaption

by introducing institutional innovations such as advisory services for farmers on regional climate change impacts. Bottom-up solutions on a community level that take into consideration the local ecosystem could increase adaption capacities (Reid 2015). Unsuitable adaptation measures, on the other hand, can cause adverse effects and reinforce existing tensions, engendering greater poverty, inequality, and conflict, rather than build resilience (Vivekananda 2011). In cities, successful pro-poor adaption that aims to reduce the vulnerability of the poor to climate change inevitably requires improved institutional capacity and effective urban governance as well as the involvement of nongovernment organizations and civil society at large into the urban governmental decision-making processes (Dodman and Satterthwaite 2008).

Future Research Directions

Similar to the contentious issues of environmental migration, scholarly opinion has yet to come together on the specifics on whether or not and how climate change impacts may exacerbate conflicts. The multiplicity of views and simultaneous lack of evidence around climate change and conflict demands further research around the role of climate drivers informing conflict and, moreover, their effect on social and ethnic tensions.

It is crucial to determine how regional and local future conflict constellations might be triggered or amplified by long-term environmental change. An analysis that is sensitive to local context is still missing (Buhaug 2015). As conflicts are increasingly intertwined globally and could lead to larger global crises (Scheffran 2015), in-depth analysis particularly in this area is of vital importance.

A multimethod approach combining qualitative and quantitative empirical research could generally help to integrate the potential of the various methods to supplement each other (Ide 2014; Obokata, Veronis, and McLeman 2014; Warner 2011). For instance, Buhaug, Gleditsch, and Theisen (2008) outline possible paths from climate change to conflict, in which they schematically separate climate change, physical impacts, regional impacts, affected sectors, and resulting conflict situations. This scheme can be regarded as a starting point for systematic analysis.

Furthermore, the category of gender should be included in the study conceptualization in future analyses of the nexus of climate change and conflict. Outbreaks of environmental conflicts have gender-differentiated causes and consequences for the reason that the affectedness of each social group to environmental change and conflict depends on their specific position. This position is shaped by resource access, income, and decision-making power, which is informed by age, ethnicity, religion, and, notably, gender. In order to comprehensively analyze conflict outbreaks, vulnerabilities, and adaptive capacities of social groups, it is therefore necessary to integrate gender as an analytical category. Even though it is now established knowledge that gender is an important variable in resource-related conflicts, only few studies so far have explicitly analyzed the gender-environment-conflict nexus. Further research can certainly help to understand the implications of gender for peace building and conflict

resolution processes in environmental conflicts (Fröhlich and Gioli 2015, 141).

Overall, the literature on future climate-related conflicts in Asia is largely focused on energy security and resource availability, owing to the fact that physical impacts of climate change will directly threaten crop yields through decreasing water and resource availability and therefore also endanger future renewable energy systems (Scheffran 2014; World Bank 2013a). It is, however, also necessary to research how social components like poverty, ethnic tensions, or migration and their interaction with physical climate impacts could increase the probability of conflicts occurring. Research on these interwoven conflict constellations is still scarce (Saha 2012). Climate impacts on poverty or migration need to be researched in order to be able to anticipate possible upcoming conflict constellations. Generally, more research on the effects of climate change impacts on poverty, migration, and ethnic tensions could form the basis for an analysis of how this set of drivers can influence conflict genesis. A stronger focus on social factors contributing to the outburst of conflicts then could help to achieve substantiated knowledge of the interrelation of the single conflict areas, which present conflict studies analyze (Buhaug, Gleditsch, and Theisen 2008; Mearns and Norton 2010).

Owing to the circumstance that more than half of the Asian population will likely live in urban agglomerations by 2020 and that these urban centers could increasingly be affected by more frequent and intense natural disasters (Shaw et al. 2016; Tanner et al. 2009), a more specific research field is needed. Research focused on the linkages between urbanization, climate change, and conflicts would provide further insights into how climate change-induced conflict could arise in urban areas.

Besides acknowledging that a possible destabilization of the Himalayan water tower poses an enormous threat to millions of people (Scheffran 2014), only few case studies so far have dealt with climate-related conflict constellations in this region with precision (Bhattacharyya and Werz 2012; Vivekananda 2011). This needs to be addressed by more substantial analyses on the potential for conflict regarding climate change-induced stress on water security, agriculture, impoverished populations, and megacities in the region (Bhattacharyya and Werz 2012). Another region that should receive more attention

in research is Central Asia, as severe climate impacts may eventually lead to unrest. Overall, the study of Schleussner et al. (2016) points future research on climate change and conflicts to ethnically fractionalized countries, as these have been the countries likely to develop armed conflicts after experiencing climate shocks in the past.

3.5 Climate Change and Migration

Many regions in Asia, particularly in the south and the east of the continent, are home to large and dynamic populations and are at the same time highly exposed to impacts of climate change. Therefore, any potential effects of climate change on human migration in these regions demand utmost attention.

Over the past years, a considerable body of research on climate-related migration has emerged. Human migration has traditionally been studied in the context of both economic (Hatton 2005; Mayda 2009) and social conditions of individuals and groups (Faist 2001; Seto 2011). More recently, the potential links between migration and environmental conditions have been investigated using a number of methods that range from empirical studies based on household surveys (Bohra-Mishra, Oppenheimer, and Hsiang 2014) to agent-based models of household migration responses (Kniveton, Smith, and Wood 2011). Issues frequently discussed include (i) a potential legal framework for the protection of environmental migrants (Biermann and Boas 2009; Williams 2008); (ii) the potential of environmental migration to induce conflict (Reuveny 2007; Warnecke, Tänzler, and Vollmer 2010.); (iii) the drivers of environmental migration or migration in general (Black et al. 2011; Hugo 2011); (iv) the difficulty to distinguish between climate-induced migration and otherwise motivated migration (such as politically or economically motivated); (v) the scope of the issue and reliable projections with regard to actual numbers and future scenarios (Döös 1997; de Sherbinin et al. 2012); and (vi) migration as a means of adaptation that should actually be perceived in a more positive manner and be facilitated by international and national policy makers (McLeman and Smit 2006; Tacoli 2009).

Besides many specific insights related to individual countries and populations, a general result that emerges

from the existing literature is a distinction between two types of environment-related migration, although hybrid forms of these two forms exist. On the one hand, short-term and short-range population displacement that tends to be caused or triggered by fast-onset environmental events, such as floods or storms. On the other hand, more permanent and longer-range migration that is driven by slow-onset events such as drought or land degradation or, more generally, by a combination of economic and social factors that may be more or less directly related to environmental changes (Black, Adger, and Arnell 2011; Brzoska and Fröhlich 2015; Kälin 2010; Waldinger and Fankhauser 2015). Cai et al. (2016) examine the relationship between temperature and international outmigration and find a statistically significant relationship only in the most agriculture-dependent countries.

In particular, floods and tropical storms, which are both likely to become more intense in the future, are already major causes of internal displacement around the world today (Yonetani 2014). At the same time, there is evidence that abrupt, short-range population movement can, at least indirectly, influence longer-range migration through the demographic changes it implies (Goldstone 2002; Kelley et al. 2015; Kniveton, Smith, and Black 2012). For instance, rural–urban migration that exceeds employment growth changes the economy of cities and can lead to social tension or conflict. These tensions can equally be influenced by a change in ethnic balances prompted by in-migration. This already highlights that a number of interlinked processes and scales need to be considered in order to reliably quantify the effect of climate change on migration. Further complexity comes from the interaction of environmental and economic drivers with demographic, political, or social drivers of migration (Obokata, Veronis, and McLeman 2014). The possibility for threshold behavior as opposed to migration as a linear response to a given driver is worth noting in this regard (Bardsley and Hugo 2010).

The Nexus of Climate Change and Migration in Asia

Given this complexity, what can be said currently about migration in Asia under a 1.5°C–2°C global warming pathway? A recent study using household survey data from Indonesia (Bohra-Mishra, Oppenheimer, and Hsiang 2014) finds that permanent migration from one province to another is strongly influenced by local temperature. This

temperature dependence is nonlinear: if local temperature is above a value of approximately 25°C, which is close to the country's average annual temperature, then further warming increases out-migration. For colder temperatures, the effect is reverse. This means that future warming on the order of 1.5°C–2°C could increase the annual probability for households to migrate by several percentage points in many of the warmer provinces and thus substantially increase the rate of permanent out-migration from these provinces.

A recent study on internal migration in Pakistan (Mueller, Gray, and Kosec 2014) uses a similar type of dataset and reaches broadly similar conclusions. Temperature—more specifically, heat stress—is the dominant environmental driver of long-term migration, while precipitation-related impacts—in this case, flooding—have only minor effects. Again, the direct effect of heat stress is mainly household income reduction, which in turn drives out-migration from the affected area. No predictions of future climate change impacts on migration are made in this study.

Contrasting with these survey-based studies, an agent-based modeling approach is used in a study of climate-related internal migration in Bangladesh (Hassani-Mahmooei and Parris 2012). The agent-based model allows accounting for the decision-making processes of individual migrants. The authors show that climate change is likely to increase migration out of the western and southern districts of the country, which are prone to drought and to floods and cyclones, respectively. Migrants would primarily move to urban areas and cities such as Dhaka, potentially challenging the economic and environmental carrying capacities of those places.

In summary, existing projections of future climate change impacts on migration in Asia are limited in number, regional scope, and predictive power. On the other hand, projections of the patterns of physical and biological climate change impacts are available at the global level and from a number of different models. It is thus worthwhile to examine projections of those climate impacts that have been identified as potential drivers of migration. Studies point to the importance of heat, flooding, and drought (Ginnetti and Franck 2014; IDMC 2012; Kjellstrom, Lemke, and Otto 2013). Coastal populations including those in Asia's highly populated mega-deltas are vulnerable to SLR and storm surges (Seto 2011). Case studies show that large

populations in Bangladesh are already being displaced or have decided to migrate due to cyclones (Islam and Hasan 2016) and riverbank erosion (Hoque Mollah and Ferdaush 2015). The various services that functioning ecosystems (both natural and managed) provide to humans are important for people's attachment to their place of residence (Adams and Adger 2013).

A recent multimodel analysis of future water availability (Schewe et al. 2014) shows that under a scenario of approximately 2.5°C global warming above preindustrial levels, there is a high likelihood of substantial reductions in water availability in central Asia. The multimodel mean indicates reductions by up to 50% particularly in Afghanistan and other Middle Eastern countries, while somewhat smaller reductions are also seen in parts of the PRC. Such reductions would increase drought frequency (Prudhomme et al. 2013) and carry risks for important ecosystems, in particular for the viability of current agricultural practices in those regions. Groundwater recharge would also be reduced particularly in Central Asia and the Middle East, thereby amplifying any existing water scarcity problems (Portmann et al. 2013). Increasing aridity and water stress is also expected for the majority of the world's island populations, including many in the maritime continent and the tropical Pacific (Karnauskas, Donnelly, and Anchukaitis 2016). At the same time, average river discharge is projected to increase in much of India and southern Pakistan, implying potential increases in flood risk (Dankers et al. 2013).

With respect to terrestrial natural ecosystems, mountainous ecosystems in the Tibetan Plateau are at risk of severe change already at or below 2°C of global warming over above preindustrial levels (Warszawski et al. 2013). Taken together with the projected impacts on agriculture, marine ecosystems, and regional sea level discussed in earlier sections of this report, it becomes clear that climate change associated with a global warming of 1.5°C–2°C will alter many, if not all, of the physical and biological processes thought of as potential environmental drivers or determinants of human mobility. These environmental factors act in the context of expected or ongoing long-term population movements. For example, a net movement of people from rural to urban areas is expected to continue regardless of any environmental drivers. Moreover, especially in India and the PRC, it

has been shown that people have tended to move out of marginal dry and mountainous regions and to move broadly into coastal areas (Seto et al. 2011; de Sherbinin et al. 2012). Thus, the number of people living in the especially vulnerable environments of coastal megacities will probably increase, just as the hazards they are facing also become exacerbated by climate change.

While climate change—even of moderate amplitude—will affect population movements in Asia, the quantitative underpinnings of these effects are still incomplete. In particular, there is a lack of quantitative studies explicitly accounting for the different processes that lead from environmental changes to migration decisions and that connect different types and scales of migration. There is also a lack of empirical data, especially from the countries of the global South that are likely to see the majority of climate impacts and that host many highly vulnerable populations. Since any models, empirical or process based, need to be underpinned with observational data, improvement both in methods and in data availability are needed to further assess and quantify the potential effects of climate change on migration in Asia.

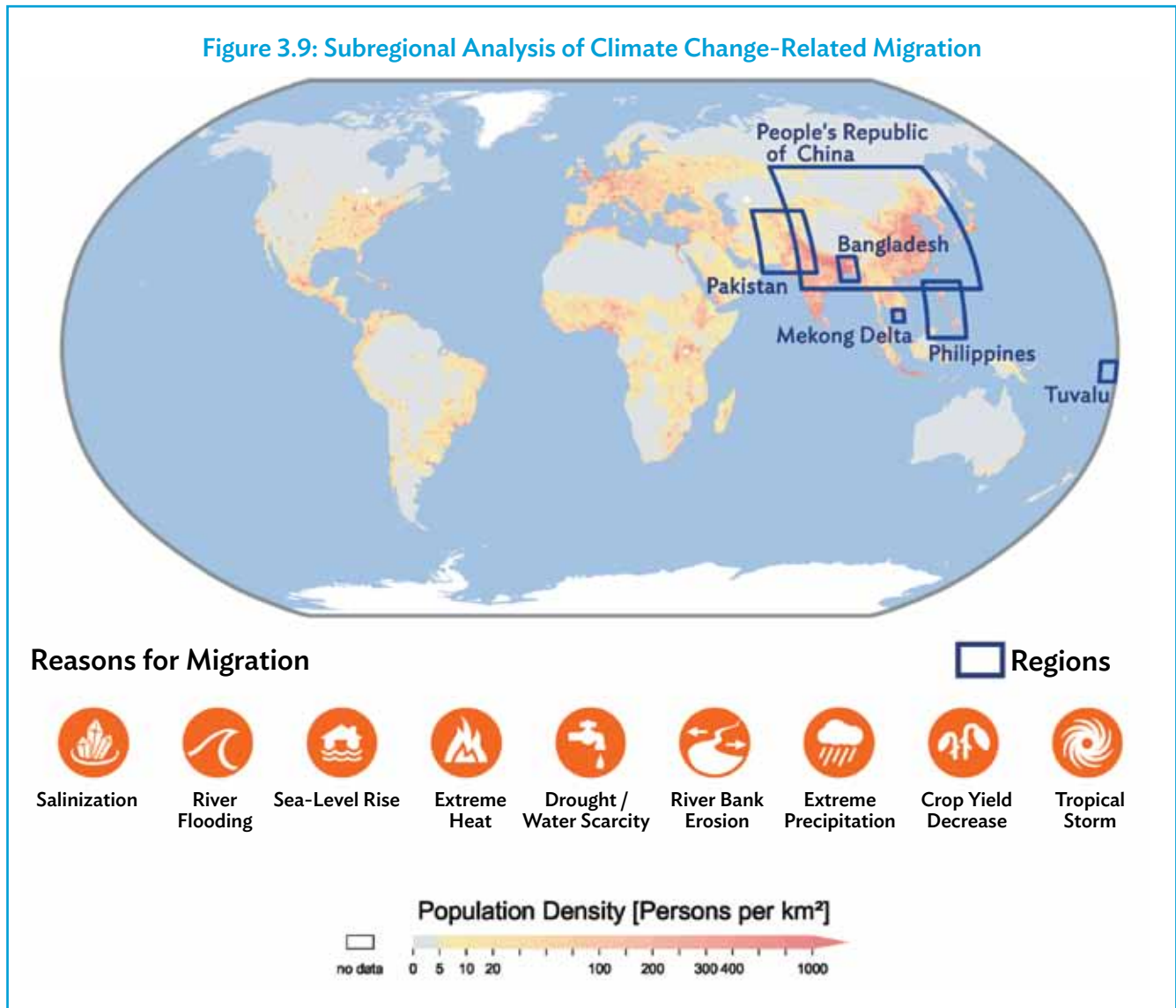
With a view to the policy implications of this type of research, it is important to note that migration can have both adverse effects, incurring high economic, social, and psychological costs to individuals and societies, as well as beneficial effects. The latter can form part of a successful adaptation strategy to changing environments by stabilizing both the sending society (e.g., through remittances) and the receiving society (e.g., through boosting the local economy) (Black et al. 2011; Waldinger and Fankhauser 2015). Whether positive or negative outcomes prevail depends not only on the causes of migration but also on the political and economic boundary conditions in the sending and receiving regions. In societies with sufficient economic resources and social empowerment, migration can contribute to successful climate change adaptation and increase the resilience of communities (Black et al. 2011; Scheffran, Marmer, and Sow 2012). On the other hand, poverty can deprive people of the option to migrate in the face of environmental challenges, leaving them “trapped” (Adger et al. 2015; Cattaneo and Peri 2015). Thus, policy makers would be well advised to consider human migration, climate protection, and poverty reduction in a joint context in order to maximize the cobenefits from efforts in all these areas.

Migration Hot Spots under Future Warming: Recent Findings

While the literature on climate migration in Asia is still limited, it provides early insights into the severity of climate change impacts on human livelihoods. It further indicates several sub-regions of the region could be particularly prone to climate-induced population movements, or have already been affected by such displacements. Many countries in Asia have high poverty rates, which, combined with insufficient governance structures, can aggravate the effects of physical and biophysical climate change impacts. The same climate impacts can therefore have completely different consequences for the local population, depending, for example, on the population’s prosperity, preparedness, or other factors within the social fabric. While in high-income groups, communities are often able to adapt to environmental hazards and mitigate risks, this is not the case in countries where poverty is widespread, people struggle to maintain their livelihood, and governance is weak. Also, disaster response measures are generally more advanced in high-income countries, whereas many very vulnerable areas lack disaster preparedness and adequate crisis management facilities.

Valuable case studies on environmental change and forced migration scenarios in a number of different Asian countries have been published in the Environmental Change and Forced Migration Scenarios (EACH-FOR) synthesis report in 2007, including studies on Bangladesh, the PRC, Kazakhstan, the Kyrgyz Republic, Tajikistan, Tuvalu and Viet Nam. Moreover, reports on climate migration and disaster-related displacement in the region have been published by the Nansen Initiative in cooperation with the Norwegian Refugee Council. Among others, they have examined community resilience capacity in South Asia (Norwegian Refugee Council 2015), developed estimates of the likelihood of disaster-induced displacement in some Asian countries (Brunei Darussalam, Cambodia, the PRC, Indonesia, the Lao PDR, Malaysia, Myanmar, and the Philippines)—but only for a limited time frame until 2018 (Lavell and Ginnetti 2014)—and assessed the options for a protection agenda as well as the different approaches and actors in the field of international cooperation and solidarity (Nansen Initiative Southeast Asian Regional Consultation 2014). One of the most comprehensive reports on climate change and migration in Asia and the Pacific has been published by ADB (ADB 2012).

Figure 3.9: Subregional Analysis of Climate Change-Related Migration



While the links between climate change and migration have not been assessed in all subregions, the following six regions (Figure 3.9) emerge as particularly prone to future climate change-related migration flows: (i) Bangladesh with the world's largest delta (the Ganges–Brahmaputra Delta); (ii) the Philippines as an island nation that is particularly vulnerable to storms (Lavell and Ginnetti 2014); (iii) the PRC, which experiences protracted droughts and at the same time hosts several megacities at its low-lying coast (Rogers and Xue 2015); (iv) the Mekong Delta, which could experience threats to food security due to SLR and floods; (v) the Indus Delta (marked as “Pakistan” in Figure 3.9), which recently has experienced strong flooding events due to extreme precipitation;

and (vi) the small island states in the Pacific (marked as “Tuvalu” in Figure 3.9), which on average rise barely above sea level and are sometimes entirely made up of atolls.

Overall, existing studies show that while a 2°C global mean temperature rise will be difficult to manage, one can assume that a 4°C increase would lead to humanitarian disasters in many nations and result in unmanageable migration flows or locked-in populations. Whereas a common challenge may first stimulate cooperation and solidarity, once impacts become so severe that ecosystems can no longer sustain the entire human population because natural resources are depleted and land is rendered uninhabitable, the opposite dynamic could take off (Reyer et al. 2015).

Bangladesh

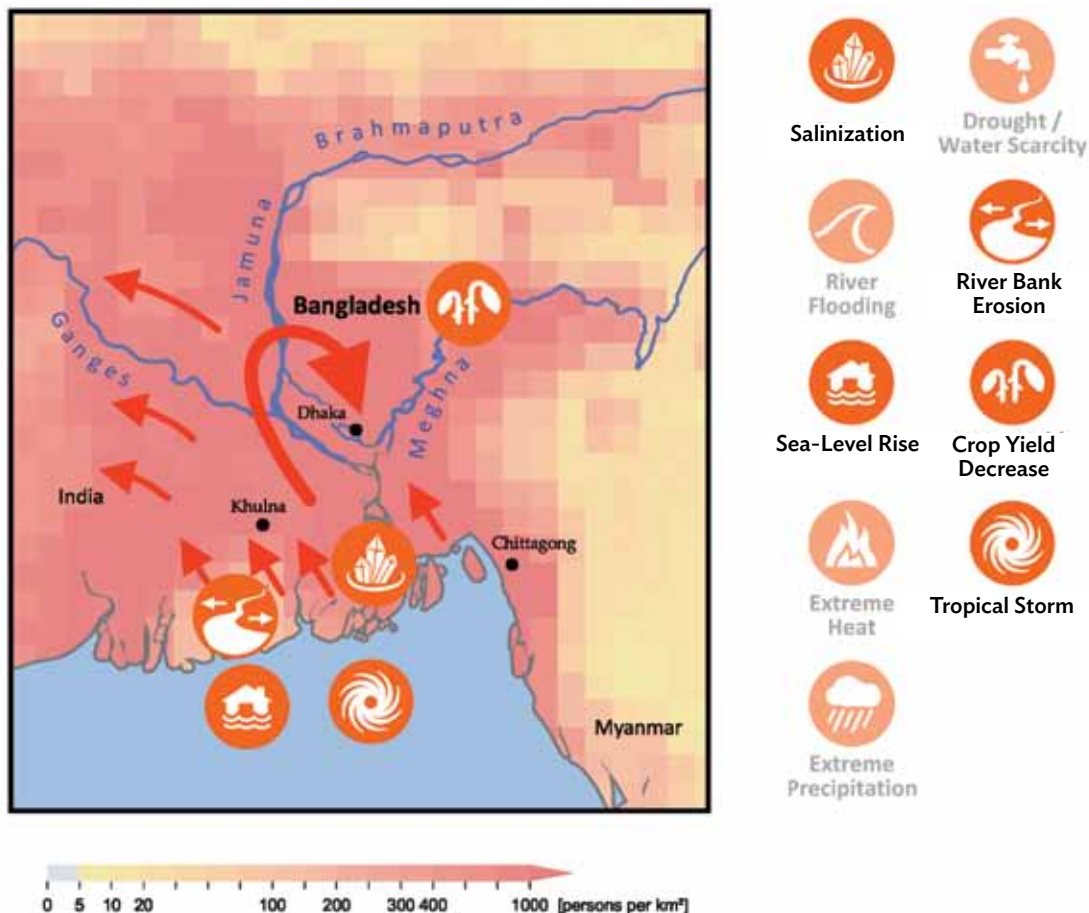
The Bay of Bengal, specifically the low-lying nation of Bangladesh, is one of the areas most severely affected by climate change (Vinke et al. 2016). High geographic vulnerability coincides with high population densities, consisting of mostly poor income groups that are heavily reliant on subsistence agriculture. As Bangladesh is particularly exposed to climate risks, the country has received much attention in the academic debate around climate migration.

A multiplicity of climatic drivers has an impact on livelihoods in Bangladesh. The Ganges–Brahmaputra Delta has long been identified as one of the hot spots of climate change effects, as it is a particularly low-lying and therefore vulnerable coastal zone. Moreover, the coastal zone is inhabited by about 130 million people that are

exposed to regular riverine flooding (IPCC 2014). With an overall population of about 160 million people (UN DESA 2015), Bangladesh is one of the world's most populous countries, but only ranks 94th in terms of surface area (Bangladesh Bureau of Statistics 2015). Bangladesh has a very high population density with an average 1,237 people per square kilometer (UN DESA 2015).

SLR could become a cause for successive out-migration. Yu et al. (2010) looked at several scenarios for SLR and concluded that in a 4°C world, a rise in sea level of 62 cm by the 2080s could result in a loss of 13% of Bangladesh's coastal land area to the sea and lead to flooding of 20% more land than currently. A 15 cm sea level rise by 2030 would lead to 3% of land loss and 6% of total flooded area increase; a 27 cm SLR would cause 6% of land loss and 10% of flooded area increase in the 2050s. This will likely

Figure 3.10: Bangladesh—Climate Impacts and Possible Migration Routes



lead to displacement of many people (Pender 2007). By the end of the century, global SLR under a Paris-consensus scenario would be roughly 40 cm and in a business-as-usual scenario about 84 cm.

Moreover, severe droughts regularly affect the country, especially in the northwestern part (Wassman et al. 2009b). Droughts impair agricultural production, causing crop losses, which are even higher than the ones resulting from flooding (Chen et al. 2012; IPCC 2014). Internal migration has already been observed in Bangladesh and while scientists disagree on future climate-induced migration patterns, the reality of migration motivated by climate impacts is generally accepted (World Bank 2013b). Due to the multicausal nature of migration, the evidence for causal links between climate change impacts and migration is limited (Walsham 2010). However, a lack of evidence of such links does not imply that climate migration does not exist. For example, despite the fact that research on migration after flooding is still limited, there is consensus that households use migration as an adaptation strategy to flooding events, by either relocating the entire household or sending individual members (Walsham 2010). Other causes for migration in Bangladesh include increasing soil and freshwater salinization (notably in the southwest) and riverbank erosion, which put an additional strain on people's livelihoods and physical health (Vinke et al. 2016). Among the drivers of migration are also tropical cyclones in the Bay of Bengal, which could increase in intensity (maximum wind speed and precipitation rates) by 2050 due to climate change under a business-as-usual (A1B) scenario (Dasgupta et al. 2010; Knutson et al. 2010). It is expected that displacement as a result of cyclones is going to rise (Ahmed et al. 2012).

Most migrants in Bangladesh migrate out of high-risk zones to nearby urban centers and to the capital Dhaka (Figure 3.10) (Naser 2011). Walsham (2010) observes that in the case of long-term or permanent migration, the majority of migrants choose cities within their home division, which is Khulna for the southwest, Chittagong for the east, and Dhaka for central Bangladesh. Another frequent migration route leads to neighboring India and to a lesser extent also to Myanmar. However, especially with regard to international migration, it is difficult to distinguish the exact reasons for migration. Generally, cross-border migration induced by environmental factors is far less common than internal migration (Walsham 2010). This

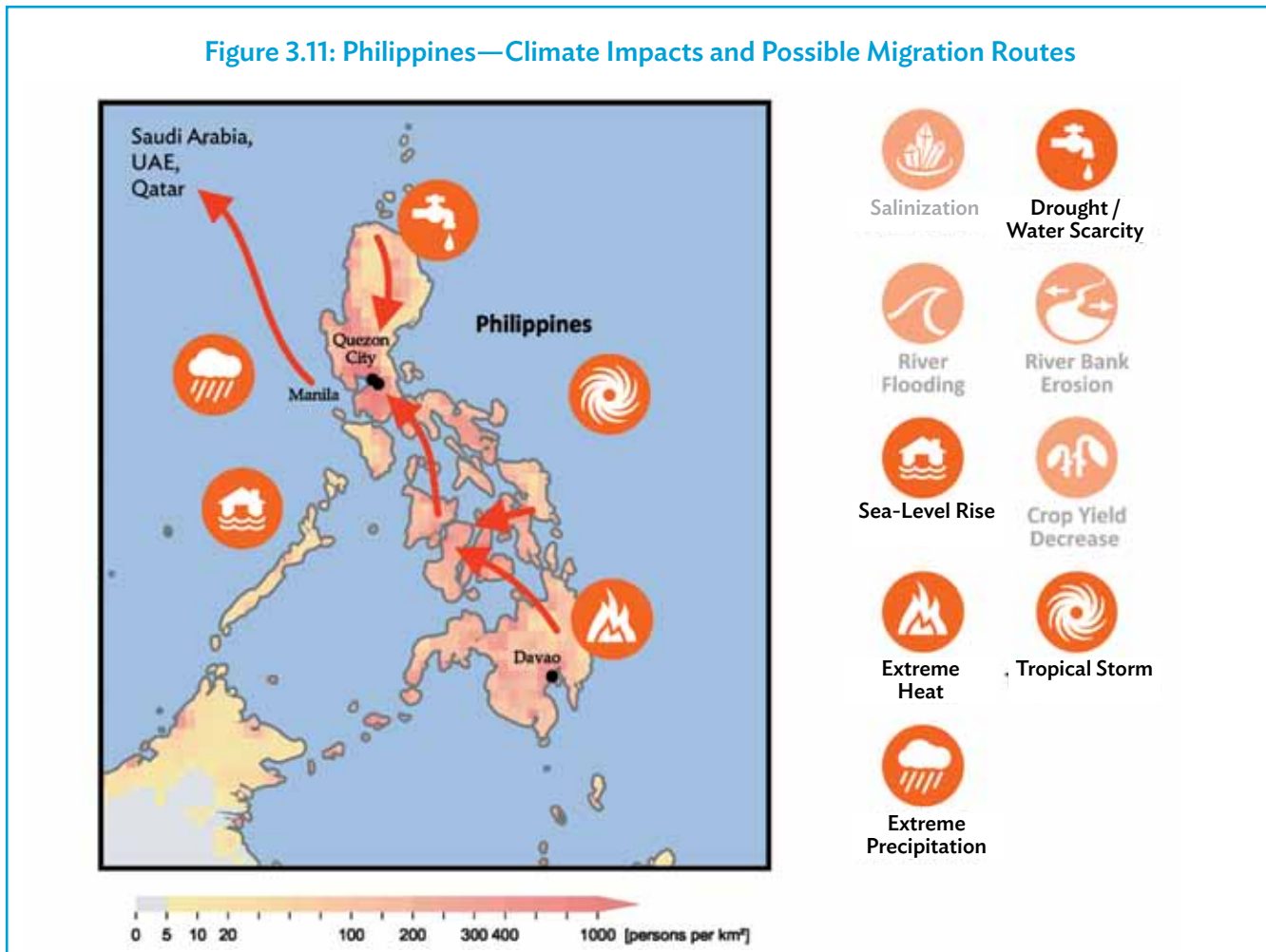
is also because international migration generally requires higher expenses and greater logistics, creating high barriers especially for the poor.

Philippines

The Philippines is particularly vulnerable to natural hazards. According to the Climate Risk Index, the Philippines was the fifth most risk-prone country in the world in 1994–2013. In 2013, it was marked the most globally affected country by natural hazards (Kreft et al. 2015). Natural disasters are expected to cause further displacement from rural to urban areas, as has already occurred in the past (Nansen Initiative 2014). Notably, typhoon Haiyan led to the displacement of about 4 million people in 2013 (Lum and Margesson 2014; Yonetani and Yuen 2014). The migration patterns observed after this catastrophe could help identify future pathways of migration as a result of worsening climate change effects on the country. As the Nansen Initiative (Harkey et al. 2014) analyzes “residents of Tacloban City went to Manila, Cebu City and other urban destinations.” The aid infrastructure and resource availability in cities is often better than in nearby rural areas, making them a point of arrival for many of the displaced.

With rice being one of the main revenue and nutrition sources in the Philippines, a link has been established between decline in rice yield and gross revenue per hectare as a result of extreme weather events and international migration. The number of total overseas Filipino workers has increased by 5 per 1,000 population for each decrease of 1 metric ton in average overall rice yield (Bordey et al. 2013). The cross-border migration of women was more affected by climate change as a push factor than the cross-border migration of men. This can be explained by the fact that the group of female migrants is often made up of unskilled agricultural workers who seek labor as, for example, housekeepers, whereas the group of male overseas migrants often consists of skilled laborers who previously worked in more technical fields, which are not as affected by climate impacts as agriculture (Bordey et al. 2013). The same study finds that internal migration decreases as a result of rice yield decline, which cannot be explained conclusively. Nonetheless, one theory is that households prefer to send migrants overseas in the face of severe economic problems, as they are more likely to earn a higher income and send remittances than if they were to migrate domestically. While the increase in overseas migration has brought some economic benefits in the

Figure 3.11: Philippines—Climate Impacts and Possible Migration Routes



form of remittances to the Philippines, especially to rural areas, there are also potential social costs of this trend. One example given by Bordey et al. (2013) is the higher number of divorces and increasing numbers of children growing up without their mothers who work abroad.

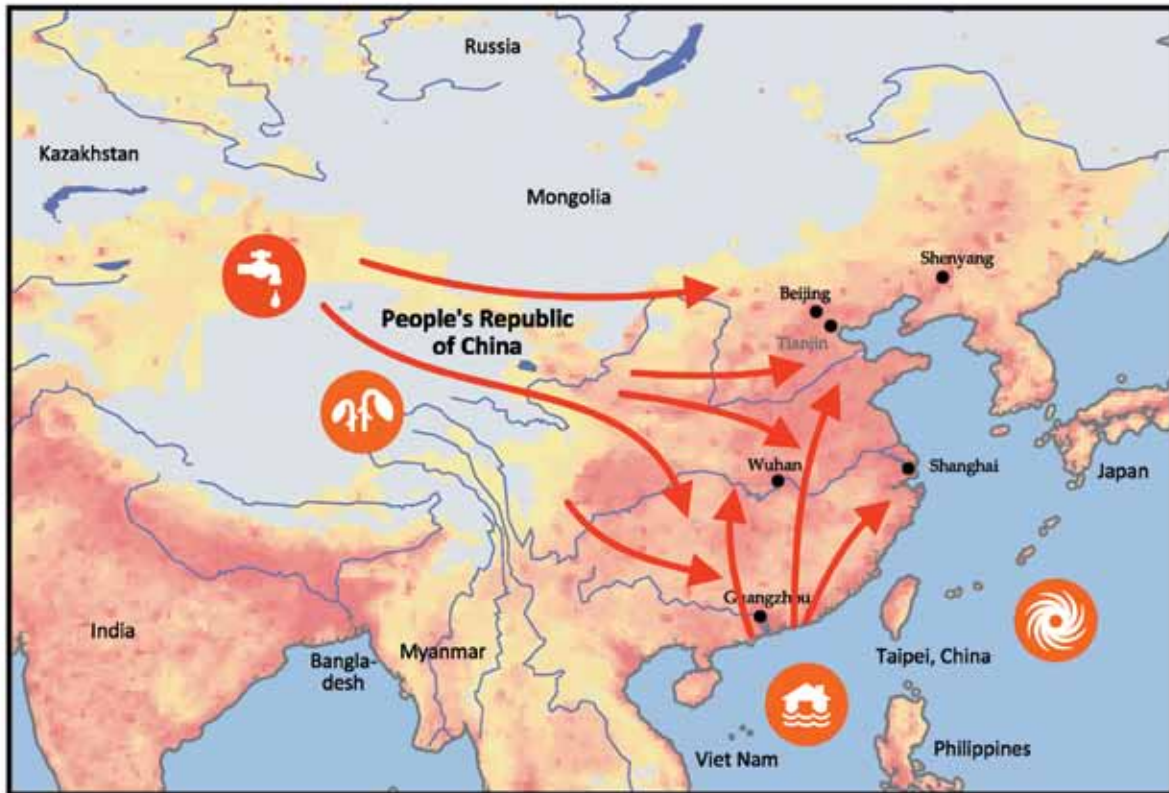
The literature on climate-induced migration in the Philippines is surprisingly scarce so far, given that the Philippines is among the countries most severely affected by climate change. More research on regional and international migrant flows is needed, as well as on the capacity of the country's big cities such as Manila and Cebu to absorb migrants after disasters. Displacement after natural disasters in the Philippines is usually localized as people want to stay as close to their homes as possible. Typically, they stay with host families outside of official government camps and return to their home in the weeks

or months following the disaster (Internal Displacement Monitoring Centre 2015). This adds to the complexity of comprehensive data accumulation on displacement. When researching the nexus of climate change and migration, difficulty also arises in distinguishing climate-related movements from traditional flows of labor migration. Additionally, it is not always possible to clearly establish whether a specific natural disaster was caused or intensified by climate change and whether a decision to migrate can therefore be attributed to climate change impacts or not.

People's Republic of China

Climate change is projected to have severe impacts on the PRC. Of particular concern are protracted droughts and desertification in the country's northern and southwestern regions, as well as water scarcity, which

Figure 3.12: People's Republic of China—Climate Impacts and Possible Migration Routes

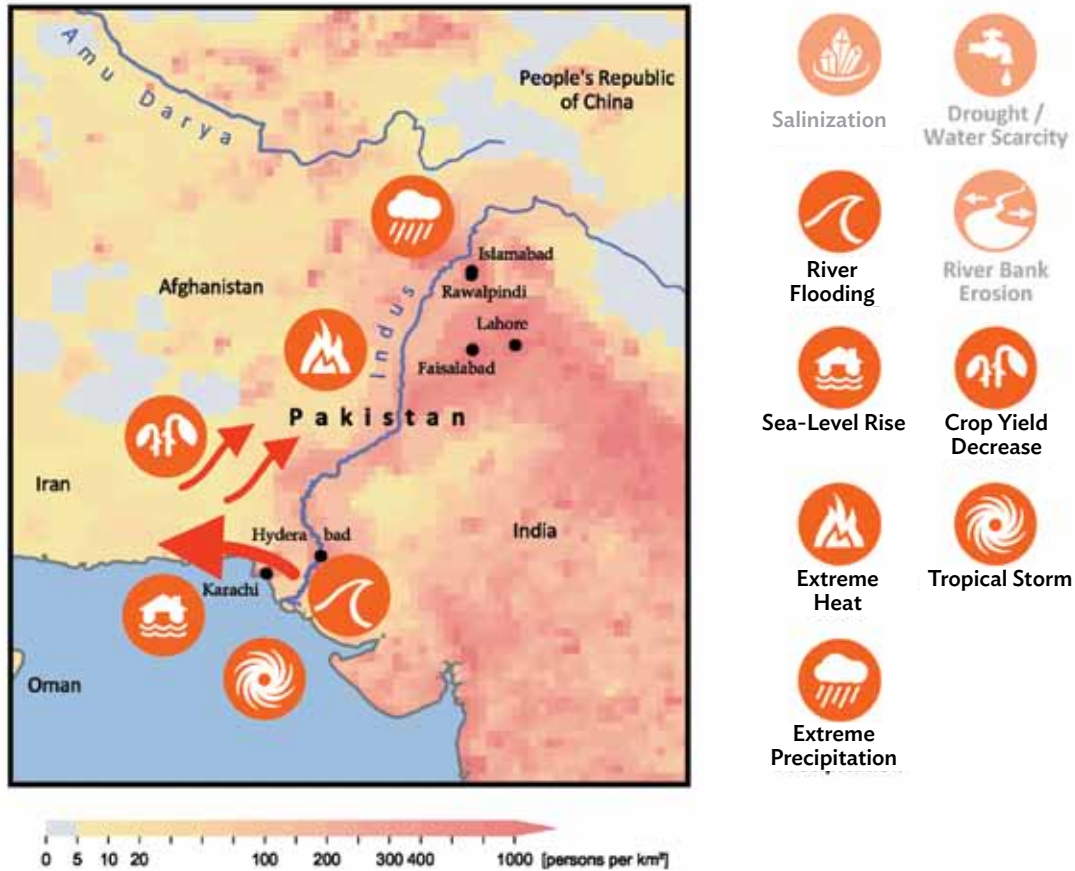


is already posing governance challenges today (Lewis 2009). The Government of the PRC is relocating people in anticipation of climate change-related environmental changes (de Sherbinin et al. 2012). However, evidence from a case study in rural PRC suggests that the resettlement activities of the government might still render households vulnerable to climate change, as many sites of relocation are in highly risk-prone areas (Rogers and Xue 2015). Also, the additional pressure of increasing numbers of households could further exhaust the natural resources of the destination area (Rogers and Xue 2015). In 2002,

Myers (2002) estimated that out of 120 million internal migrants in the PRC at least 6 million should be viewed as environmental migrants as their out-migration was induced by declining crop yields.

Generally, it is difficult to find solid evidence on climate-induced migration within the PRC, as data are scarce or not accessible. Even if there were sufficient datasets on migration flows, it would still be difficult to disentangle migration flows motivated by economic and environmental factors. Contrary to many other countries, the apparently

Figure 3.13: Indus Delta—Climate Impacts and Possible Migration Routes



predominant migration pathway in the PRC is not from the coastal zones land inwards, but from rural inland areas into particularly vulnerable coastal zones, where most of the important urban and economic centers of the PRC are located (see Figure 3.12). Migrants from rural areas seek employment in the cities which is partially encouraged in order to foster economic growth along the strategically important coastline (McGranahan, Balk, and Anderson 2007). These demographic and economic changes have led to the concentration of risk exposure to some extreme weather phenomena (e.g., storms and floods) in urban centers. Flood and storm-related displacement in the PRC mostly takes place in dense urban areas along the coast (Lavell and Ginnetti 2014).

Three regions are particularly prone to climate-induced migration: the upper regions of the Yangtze and Yellow

river, where the population might be forced toward the Qinghai–Tibet plateau or toward cities on the country’s east coast due to soil degradation and dams; the northern and northwestern parts of the PRC, where desertification and droughts are threatening farmers’ livelihoods; and the southeastern coastal regions, where typhoons and flooding are likely to increase (ADB 2012).

Indus Delta

Over the past 3 decades, the Indus Delta region has experienced extreme precipitation, more frequent cyclones and connected flooding events, prolonged heat waves, as well as severe droughts (Rasul et al. 2012). In 2010, heavy precipitation that has been linked to an unusual pattern of the jet stream, resulted in disastrous floods (Sayama et al. 2012). The 2010 floods in Pakistan caused temporary displacement of about 14 million people, with 200,000

moving to internal displacement camps (Mueller, Gray, and Kosec 2014). Moreover, agricultural losses accumulated to \$1 billion. Furthermore, the combination of periods of drought followed by extreme precipitation and floods has displaced several hundreds of thousands of Pakistanis, as for instance after the 2011 floods in Sindh Province (Khan et al. 2016).

Seawater intrusion and overexploitation of groundwater is causing the once fertile agricultural land to deteriorate in quality, which many people depend on for their livelihoods. Melting glaciers in the north of Pakistan result in additional river flooding (Rasul et al. 2012). Precipitation patterns have become more difficult to predict as a result of extreme climate anomalies. While precipitation in Pakistan has always experienced large-scale variability, the past few decades have shown a significant increase in both dry and wet spells, with northern Pakistan experiencing a significant decline in rainfall notably during the winter season, whereas the southern Indus Delta has seen a moderate increase in rainfall, which mainly results from frequent local heavy precipitation spells (Rasul et al. 2012). Furthermore, climate change could impact the variability of the monsoon and lead to changes in the intensity and timing of precipitation (Atta-ur-Rehman et al. 2013). This would further aggravate the water stress already present in the region today, as farmers have to be able to plan for the monsoon onset and withdrawal in order to effectively farm their land (e.g., plowing day).

In a study based on individual-level survey information gathered over more than 2 decades, Mueller, Gray, and Kosec (2014) found that besides water-related impacts, heat stress leads to a substantial increase in long-term migration. Extreme heat mostly negatively affected agricultural income (-33%), but also caused losses in nonagricultural income (-16%) (Mueller, Gray, and Kosec 2014). Whereas flooding events attract high relief efforts, heat waves have so far largely been neglected.

Mallah (2013) argues that in Pakistan climate change-induced migration takes place mainly within the country. In the aftermath of past environmental disasters, the Indus Delta's urban hub Karachi has been identified as a main destination. This is consistent with the general literature on climate-induced migration, which highlights the pattern of people migrating to urban centers first, before some eventually move further and cross international

borders. Overall, the literature on climate-related migration, migratory routes as well as the interaction between decisions to migrate and climate change impacts on livelihoods in the Indus Delta remains underdeveloped.

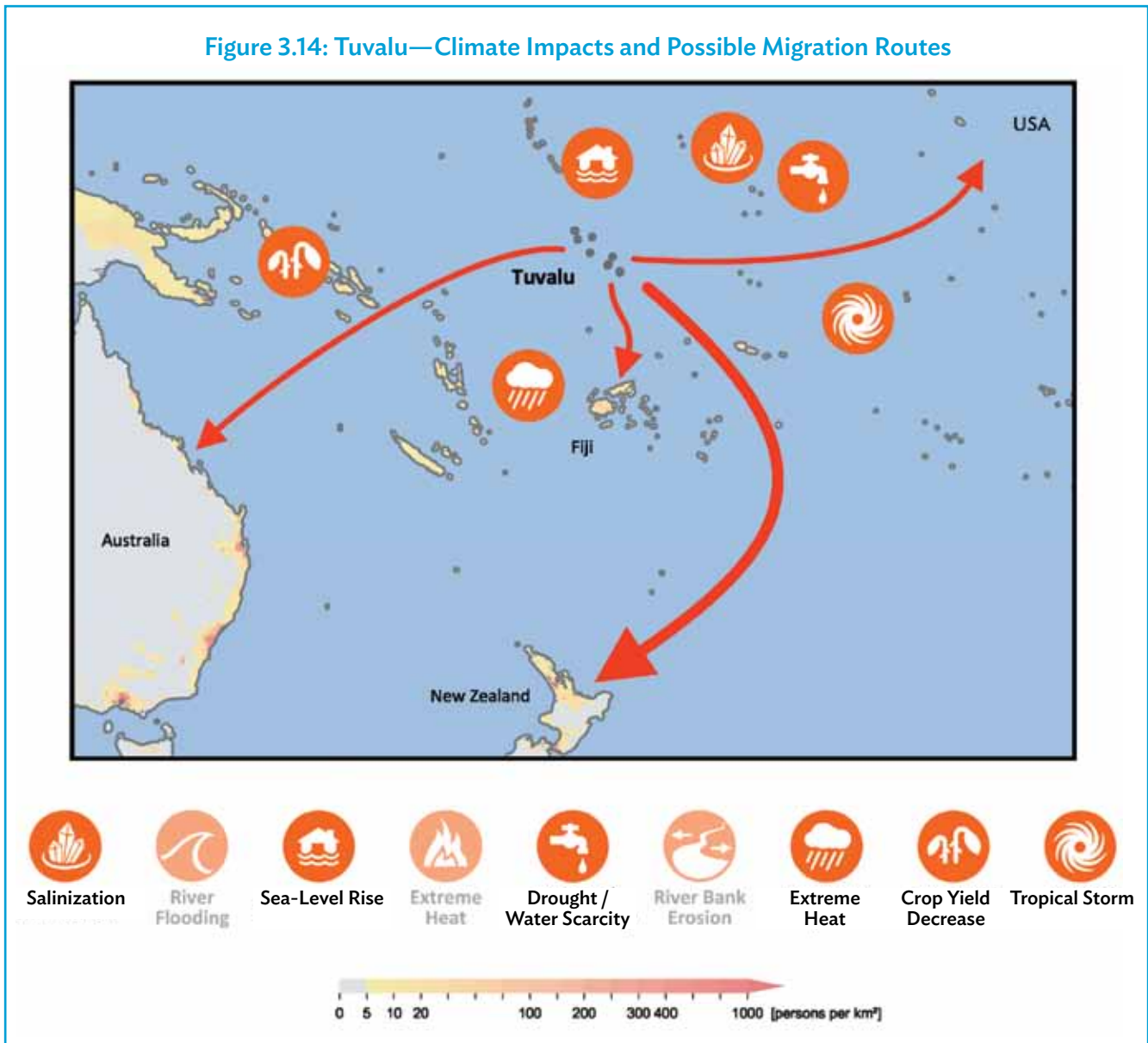
Pacific Small Island States

Small island states in the Pacific Ocean are especially vulnerable to the impacts of climate change, as they have very limited options for adaptation. Some islands consist exclusively of atolls barely rising above sea level, which might lead to the loss of their territory with continued SLR. Their limited spatial capacity often makes internal relocation unfeasible, mostly only leaving the option of migrating to other countries. What furthermore complicates the situation for the small island states is the legal question regarding their statehood that arises were their territory to be submerged by water. Territory is one of the three constitutive elements (population, authority, and state territory) of a state, and, while it is generally accepted that a state can continue to exist even in the event of the loss of one or two of those elements, the complete loss of territory would put heavy constraints on its statehood.

Besides SLR, one of the major threats posed to Tuvalu and other small island states is severe storm surges and related flooding (Haigh et al. 2011; Komar and Allan 2008). In its fifth assessment report in 2014, the IPCC stated that the rate of relative SLR in Tuvalu (on its main atoll Funafuti) has been about three times higher than the global average. Coastal flooding threatens low-lying areas and is expected to increase in occurrence and intensity. Saltwater intrusion due to SLR and rising coastal erosion is also threatening the groundwater supply of the small island states (Pacific Small Island Developing States 2009; UNESCO International Hydrological Programme 2015).

As for other regions, people of the Pacific islands are expected to primarily migrate to cities when being affected by environmental events (Campbell 2010, 2014). Locke (2009) found strong evidence that movements from predominantly rural to urban islands have been incentivized by a combination of climate change effects and other factors. Rural-urban migration seems the most probable. However, because of close ties to their land (often also of religious nature), it is likely that islanders will have difficulty sustaining their community and culture (Locke 2009; Mortreux and Barnett 2009). Nonetheless, this is likely to be even more difficult in the case of international

Figure 3.14: Tuvalu—Climate Impacts and Possible Migration Routes



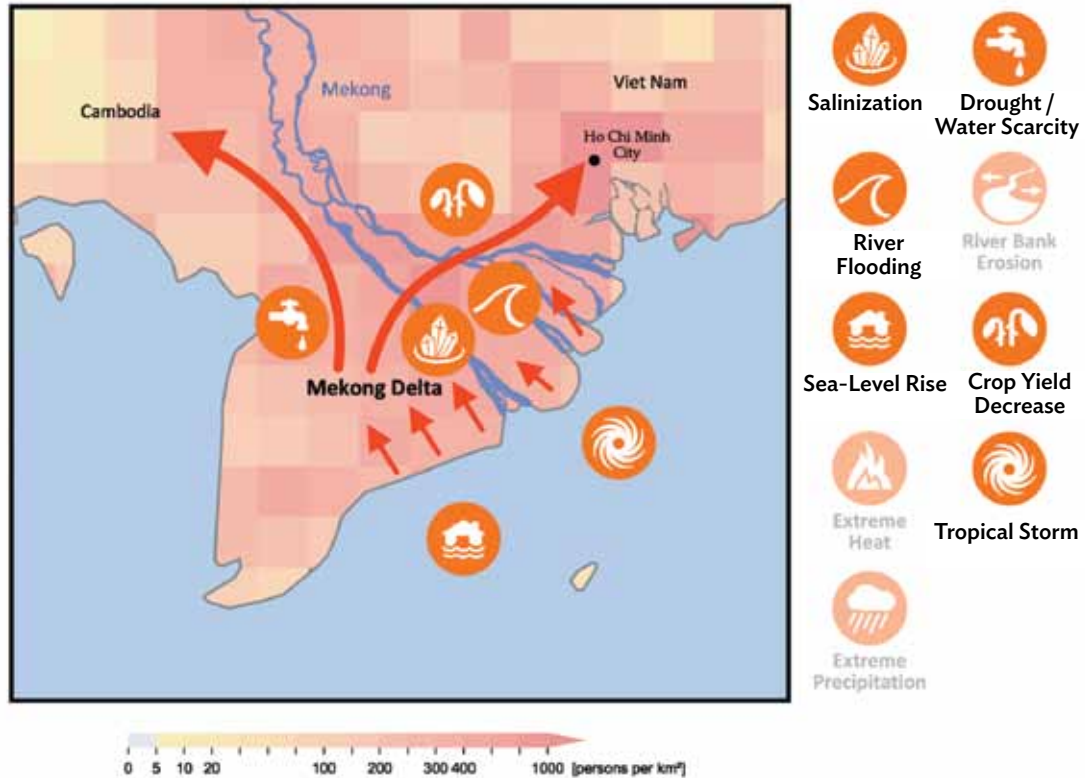
migration, a probable movement as small islands only have limited options to migrate to other Pacific island countries (Locke 2009). One point of destination is Fiji, which has a higher elevation than other small island states and can therefore provide safe refuge, within a similar geographic setting. The Government of Kiribati, for instance, has already bought 20 km² of land on Vanua Levu, Fiji. Other possibilities include resettlement in distant countries such as Australia, New Zealand, or even the United States. Yet, these options prove to be legally difficult not least due to ongoing disputes between these nations (Shen and

Binns 2012). Looking at the possible uninhabitability of atolls in various island states in the Pacific, it is clear that for the preservation of culture and of self-determination over whether to stay or to migrate, every tenth of a degree increase in warming will make a significant difference.

Mekong Delta in Viet Nam

The Mekong Delta in Viet Nam is one of the most densely populated regions on earth. There are more than 18 million people living in the Vietnamese portion of the delta, accounting for a fifth of the country's population. After

Figure 3.15: Mekong Delta—Climate Impacts and Possible Migration Routes



initially having been a popular migration destination due to its fertile soil, this trend has been reversed in the past years. Increasingly, migration away from the delta to big cities and seasonal migration within the delta are being observed (Dun 2011). The Mekong Delta is especially at risk of flooding. Floods occur regularly and play an important role for the economic activity of this area as it is a major rice planting area and rice requires a lot of water. Over 50% of Viet Nam's staple food is being produced in the delta and more than 60% of the country's shrimp production takes place here (Dun 2011). However, floods that exceed the normal flood depth range (0.5–4 m) can have damaging effects (Warner 2010). During the past 4 decades, flood events that went beyond the critical threshold of 4 m have increased, leaving the delta and its inhabitants vulnerable to the consequences (Le et al. 2007; Warner 2010). In the long term, SLR, tropical storms, and flooding events could aggravate the situation in the delta for people whose livelihoods are closely intertwined with ecosystem services (notably the agriculture and fishery sectors) (Warner 2010). If no comprehensive adaptation

measures are taken, climate impacts will increasingly contribute to the migration decision of many people in the Mekong area (Dun 2011). Already today, people move to urban centers during the flooding season. This may intensify as climate impacts become more severe in the future (Costa, Schwerdtner, and Paragay 2013; Dun 2011). A case study conducted in 2009 found evidence that regular flooding of the Mekong Delta can lead to individual migration decisions. Parallel to this, the government is already resettling parts of the population because of their exposure to those environmental impacts (Dun 2011). The largest number of people exposed to floods lives in the central part of Viet Nam (Lavell and Ginnetti 2014).

Even a moderate SLR would have severe impacts on the delta; parts of the delta could be completely flooded seasonally (Chaudhry and Ruyschaert 2007). Other hazards threatening livelihoods in the Mekong Delta include increasing intensity of droughts due to changing rainfall patterns, increased evaporation resulting from higher temperatures, soil salinization, and an increased risk

Table 3.5: Recommendations to Address Climate Change Induced Migration

Time Frame	Output	Selected Activities
Short Term	Improve the empirical basis for policy and planning	Strengthen data collection and management. Build more robust modeling of climate-induced migration at subregional and national levels. Develop and adopt best practice.
	Capacity development	Improve capacity building in the development and operationalization of labor migration policy in both origin and destination countries. Improve governance of migration systems to discourage exploitation of migrant population. Build capacity in disaster preparedness and the management of evacuation of large numbers of people.
	Strengthen institutional mechanisms	Strengthen mechanisms for environmental migration, integrating international responses in coordination and improving relocation services.
Medium Term	Financing	Create or expand a regional fund responding to impacts of climate change across the region. Support regional consultative processes on migration.
Long Term	Migration as a development strategy	Identify skills of local workers in demand in international markets. Provide appropriate training to potential migrants. Identify suitable destination labor markets. Develop efficient transport linkage.

Source: Adapted from ADB. 2012. *Addressing Climate Change and Migration in Asia and the Pacific*. Manila.

for more intense typhoons (Chaudhry and Ruyschaert 2007; Yonetani 2014). Smajgl et al. (2015) estimate that the predicted migration patterns in the Mekong Delta as a response to SLR will put pressure on peri-urban areas in the short term, while increasing the likelihood of international migration in the long term. Up until today, disaster-related displacement in the Mekong Delta has largely been linked to heavy precipitation events (Lavell and Ginnetti 2014).

Climate Change and Migration: A Preliminary List of Possible Adaptation Measures

In its important study, ADB (2012) presents a number of short-term, medium-term, and long-term recommendations aimed at addressing the projected impacts of climate change on migration. These are summarized in Table 3.5.

Climate Change Migration: Future Research Directions

While climate-induced migration has emerged as an important research field, there are still considerable knowledge gaps which call for further analysis.

Climate Impacts as Drivers of Migration

Drivers of climate migration should be studied jointly to allow research to arrive at an understanding of the interaction of climate impacts with other drivers of migration, such as economic and political causes. Generally, two categories of climate impacts can be distinguished in the analysis of migration triggers: slow-onset events (e.g., droughts and water stress) and sudden events (e.g., floods and storms). The topic of migratory responses to gradual climate change, such as desertification, salinization, and drying of soils, deserves more attention. To date, much research concentrates on the effects of sudden weather shocks, while the interaction of gradual climate change with migratory movements requires long-term studies. These could offer valuable insights into understanding migration patterns as a whole.

While the impacts of sudden events are better represented in the climate migration literature, there is still room for further research. In places of origin, observed push factors include the dynamics of land gain and land loss in the coastal regions and floods that cause protracted

waterlogging (for Bangladesh, see Walsham 2010). Considerable data are available on displacements after natural disasters such as tropical storms and floods which should be used for further analysis.

Migration Patterns

More research is needed on the decision-making processes of migrants. The migration and climate change literature implies that there is still a lack of knowledge about possible destinations for environmental migration (Tacoli 2009). In order to better anticipate and manage migration, it is necessary to determine which cities and metropolitan areas will become or continue to be points of arrival.

In many cases, migrants lack information on what to expect at their points of arrival. This calls for a better information policy of states and at the same time creates opportunities for practitioners to better navigate migration flows, at least as far as this is possible. A more in-depth understanding of this issue could help to anticipate and manage migration. As a consequence, more effective policies could be shaped in places of origin as well as in receiving urban centers.

Climate Migration and Cities

Temporary migration to the city for employment might evolve into permanent migration. With population growth and the influx of other migrants, seasonal migrants might find themselves unable to compete for jobs on a seasonal basis. Yet, failing to find work abroad, they are likely to be trapped in the urban spaces, forced to accept the most menial work in order to support their families. The links behind these kinds of dynamics is worth studying further, especially considering that air pollution, malfunctioning water supply, and worsening housing conditions render urban populations vulnerable to illness and a life in poverty.

Gender and Climate Migration

One important point that should not be neglected is the gender–climate migration nexus which so far has not received adequate attention, even though a slight increase in awareness has been observed over the past years (D’Ooge 2008; Enarson, Fothergill, and Peek 2007; Hunter and David 2009). Not all data on climate-induced migration differentiate between men and women; this is, however, very important in order to be able to detect the differences in vulnerability and migration choices of men and women. It should be ensured from the beginning that separate numbers are being stated for men and women.

This will facilitate a better understanding of specific migration motivations but also provide more insight into the different situations in which men and women find themselves in the face of climate change impacts. Young men are often the ones to migrate first in order to provide for their household and send remittances back home. However, for some jobs or migrant destinations, this is not the case. One example would be the influx of Southeast Asian female workers into the Gulf region, where they usually work as housekeepers (Sabban 2002). Without an improved understanding of the gender dimension in the climate migration nexus, it will be very difficult to design suitable policies.

Adaptive Capacity of Climate Migration

In the past, literature on the migration–climate change nexus has been criticized for disregarding the potential positive aspects of migration. With an increased acknowledgment of migration as an “adaptation” strategy, this criticism has been calmed. Nearly all articles published on this topic at least mention, if not highlight, the adaptive capacity of migration in the face of climate hazards (see, e.g., Bardsley and Hugo 2010; Campbell 2010; Warner 2010). Having established this fact, scientists should further examine how migration can best be managed and even facilitated for out-migration from high-risk zones, in order to exploit its full positive capacity. In terms of practical and applied research, notably more effort could be spent on identifying best practices of successfully motivating people to move to less vulnerable areas, for example to nondeltaic regions.

Further insights on resilience and the adaptive capacity of migration could be gained from linking research on climate migration to the research on remittances. Remittances play into a household’s decision whether to migrate or not and can enhance the adaptive capacity of a household (Asis 2006). Such payment could render out-migration of more members unnecessary and maybe even enable a future return of the emigrated household member. Adding to this, existing research on the cooperation among migrants and the links between the diaspora and home communities could be reflected within climate migration studies. Migrants’ associations and nongovernment organizations can influence individual decision making and play an important role in defining migration routes (Asis 2006). Therefore, a deeper understanding of existing networks could further the general understanding of the phenomenon.

As Obokata, Veronis, and McLeman (2014) point out, research should not be limited to climate migrants but also include potentially trapped populations of people who may not have the option of migrating. This can have various reasons, such as a depletion of financial resources needed for relocation (Obokata, Veronis, and McLeman 2014). It is also advisable to further integrate migrants in the research conducted, as they are experts on their own lives and should be viewed as facilitators in the process of understanding this complex phenomenon of climate migration.

In conclusion, while uncertainties prevail over the nexus of climate change and migration, it is important to note that as climate impacts intensify, drivers for out-migration from vulnerable areas will become more prevalent. The research community should thus engage in an expanded assessment especially of internal migration, taking into account further pressures on urban areas. Such forms of anticipatory research, acknowledging methodological difficulties, could greatly aid policy formation to avoid mismanaged migration and human hardship.

3.6 Climate Change and Trade Networks

As indicated in Part 2 of this report, extreme weather events are projected to become more frequent and intense under climate change. A sharply rising trend in the costs incurred locally by extreme weather events can already be observed today (Ward and Ranger 2010). Extreme weather events can wreak havoc on a company's supply chain, shutting down its production facilities or preventing its suppliers or logistics providers from fulfilling their commitments. These production losses occur abruptly and are difficult to anticipate. Moreover, the resulting supply shortages can propagate through the globalized network of supply connections (hereafter "trade network") leading to cascading losses (Levermann 2014). Hence, the economic impacts of local extreme events are by no means confined to national boundaries but might have repercussions not only across the Asia and Pacific region, but across the globe. For example, droughts in the United States, the Russian Federation, and Australia; floods in Thailand; and typhoons in the Philippines in recent years have resulted in production losses and steep price increases globally for a

wide range of goods ranging from wheat to computer chips (The Economist 2012).

Although firms implement local adaptation measures tailored to their respective supply chains, it is unknown and uncharted how the different strategies interact with each other and affect global supply networks. Recent extreme weather events experienced in the region indicate that existing company-specific measures taken to date are not sufficient to mitigate supply shortage cascades. Accordingly, several countries have initiated efforts to design strategies for increasing the resilience of the regional supply chains (Government of the United States 2012).

Nowadays, resilient supply chains are of extreme strategic importance to maintain economic competitiveness and are expected to become even more important in the future (Christopher and Peck 2004; Lee 2004; Sheffi and Rice 2005). Well-designed adaptation strategies are particularly important for most countries of Asia and the Pacific, as their economic development and growth significantly depends on trade. Increased world market integration will also expose them to systemic risk of cascading supply losses. As companies in developing countries might lack the capacities to develop adaptation strategies, public sector policies can play a crucial role in supporting them and setting adequate incentives for managing this risk in an optimal way (IPCC 2014). As cascading production losses do not respect national borders, national policies have to be well coordinated or developed in multilateral efforts.

This section first demonstrates the potential impacts of disaster-induced production losses traveling along the supply chains in Asia and the Pacific. Then, we summarize the main factors contributing to an increased vulnerability of the global supply network and refer to possible adaptation measures that may alleviate these vulnerabilities. Eventually, we conclude by identifying the research needed to single out policy-relevant, suitable adaptation concepts.

Assessing the Climate Impacts on the Asian Supply Chains

As discussed earlier in Part 2, recent studies reveal that flood risk is projected to increase significantly in Southeast Asia and India under global warming. Since industries in this region are highly interlinked, localized disasters may have transnational repercussions.

Box 3.4: Estimating Production Shortage Interdependencies

The analysis of potential supply chain cascades is conducted by the network measure production shortage interdependency (PSI; Glanemann et al. 2016) and the dynamic supply network model *Acclimate* (Bierkandt et al. 2014; Wenz et al. 2014; Otto et al. 2016).

PSI belongs to the class of centrality measures determining the importance of one vertex, or producer, for the rest of the network to be functional. The index assesses and tracks the input dependence of other producers on a particular supplier from one supply chain layer to the next. Thereby, PSI allows for alternative assumptions on the substitutability of the scarce inputs. The illustrations of the potential production shortages (see Figure 3.16 of this report) are based on the assumption that substitutability is rendered difficult or even impossible, which may be the outcome of an extreme weather event. The unexpectedness of extreme weather events limits the time to reorganize supply and to prepare for supply shortages. The capability to reorganize supply is furthermore limited the more the producers rely on lean production practices. The greater the substitutability of the inputs, the smaller the production shortage dependencies.

Acclimate is an agent-based network model that simulates decisions and interactions by consumers and producers in the aftermath of a production shock. On the same time scale as the local events, the model explores immediate response dynamics as well as the subsequent recovery phase of the economic network. On a daily timescale, each agent optimizes its purchase, demand distribution, as well as production and supply distribution to maximize its revenue. Unlike general equilibrium models, it puts a focus on short-term disequilibrium effects and resolves the transition dynamics toward a new postshock equilibrium. Thus, it can be used to analyze short-term effects inaccessible by equilibrium-based modeling approaches.

Sources: R. Bierkandt et al. 2014. *Acclimate – A Model for Economic Damage Propagation. Part I: Basic Formulation of Damage Transfer Within a Global Supply Network and Damage Conserving Dynamics. Environment Systems and Decisions. 34(4). pp. 507–524*; N. Glanemann et al. 2016. *Abrupt Events and the Global Supply Network: A Novel Measure for Cascading Production Losses*. Potsdam: Potsdam Institute for Climate Impacts Research; C. Otto et al. 2016. *Modeling Loss-Propagation in the Global Supply Network: The Dynamic Agent-Based Model Acclimate*. Potsdam Institute for Climate Impacts Research; L. Wenz et al. 2014. *Acclimate – A Model of Economic Damage Propagation. Part II: A Dynamic Formulation of the Backward Effects of Disaster Induced Production Failures in the Global Supply Network. Environment Systems and Decisions. 34(1). pp.525–539*.

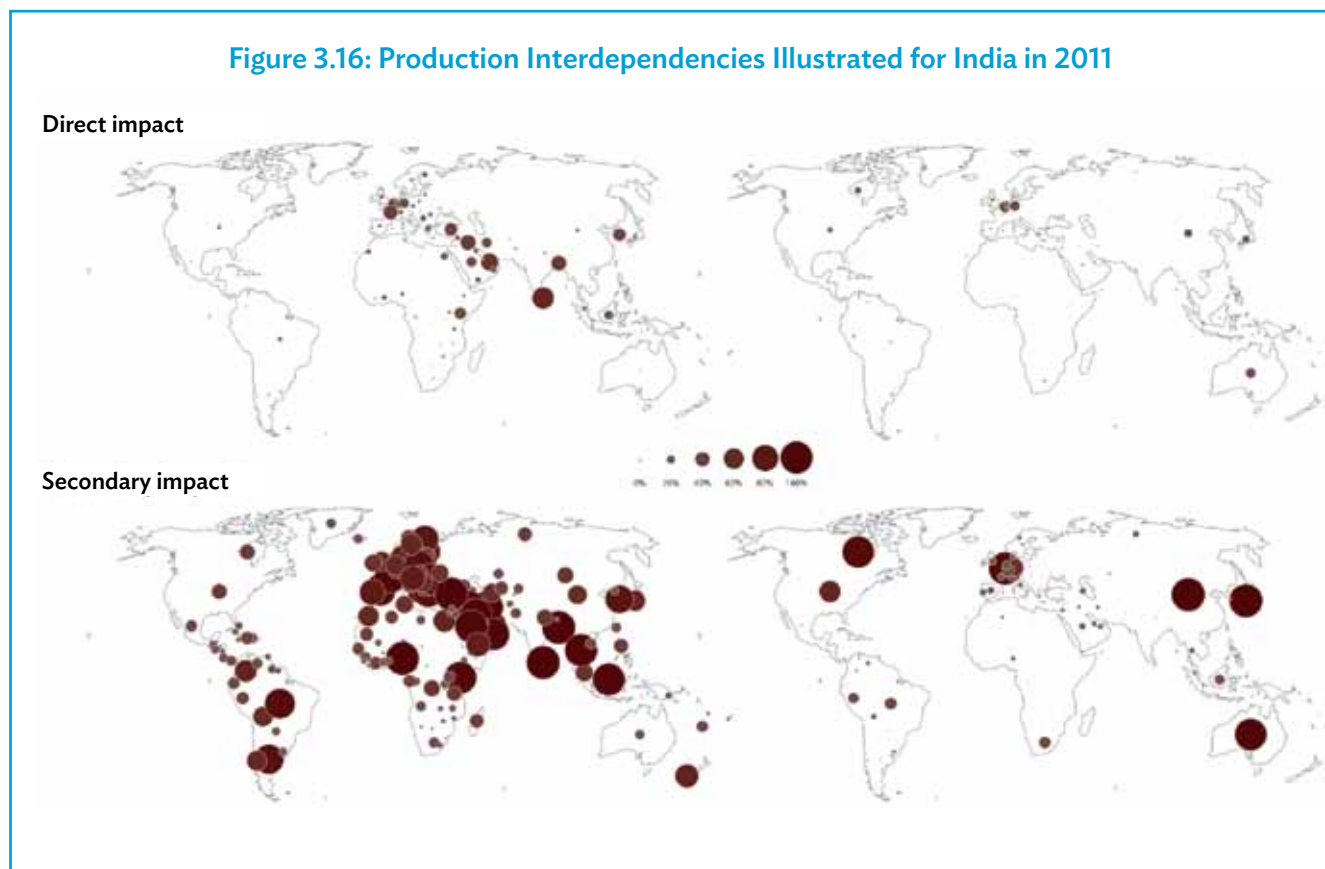
Research on the impacts that extreme weather events can have on the global trade network is at its very beginning. Transmission of production losses through the input–output linkages between firms has been identified as a key mechanism that has the potential to make small, localized production shocks snowball into macroeconomic downturns (Acemoglu, Ozdaglar, and Tahbaz-Salehi 2014; Gabaix 2011). The likelihood and duration of such a loss cascade depend on certain properties of the affected parts of the supply network such as the range, connectivity, and trade volumes of the disturbed supply chains (Acemoglu et al. 2012; Wenz and Levermann 2016).

Based on these insights, Glanemann et al. (2016) develop a measure of the production shortage interdependency (PSI) between countries (Box 3.4). This measure can be used to identify the degree to which national economies are connected with some other country, and thus are potentially vulnerable to disaster-induced production shocks in this country. For example, a reduction of India's

exports directly affects production in the PRC and many other Southeast Asian countries, unless the direct trade partners are well prepared to respond to possible supply shortages (Figure 3.16, left column, top panel). Production shortages in those countries might then cut down their trade partners' production. Apart from a few least developed countries, this secondary impact affects all countries worldwide (Figure 3.16, left column, bottom panel).

PSI also quantifies the state of some countries' import dependencies. For example, India's production is contingent on the direct imports from economically thriving countries like Australia, Canada, the PRC, Japan, and the United States (Figure 3.16, right column, top panel). These countries' production, however, also depends on some other countries' exports. Taking these indirect effects into account, it is then found that India's production is also reliant on other highly vulnerable countries like Indonesia and Thailand (Figure 3.16, right column, bottom panel).

Figure 3.16: Production Interdependencies Illustrated for India in 2011



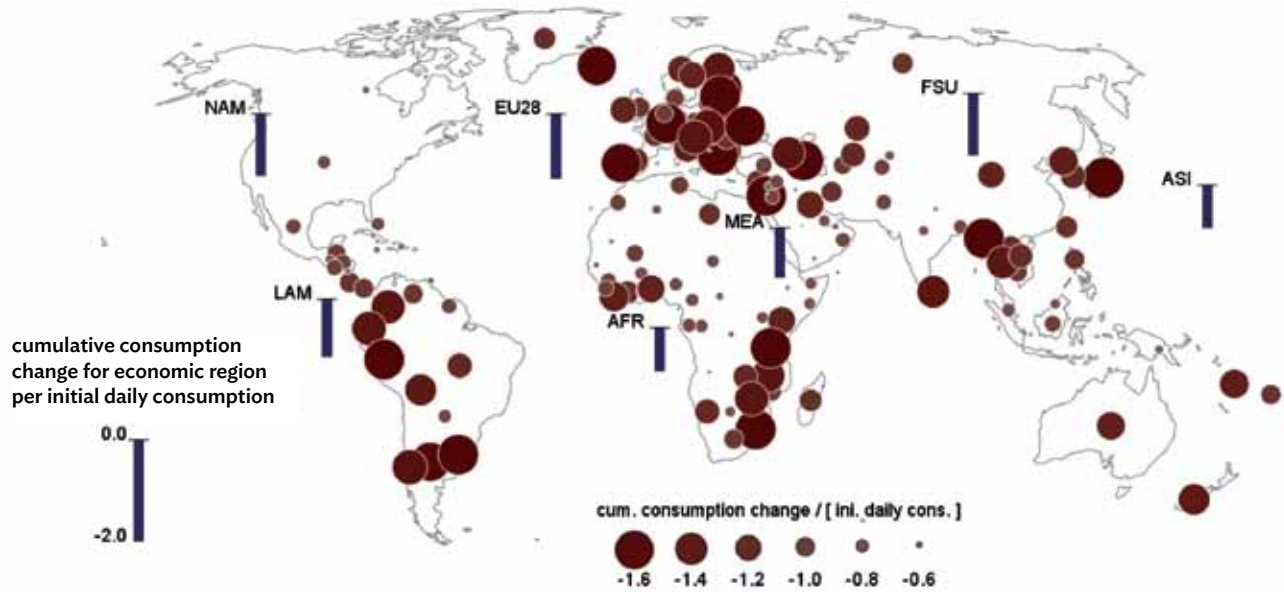
This static analysis shows that the developing countries in Asia might hamper each other's economic growth in a changing climate with more frequent and more devastating weather extremes.

A dynamic analysis providing insights into the propagation of supply shortages is offered by the trade network simulation model Acclimate (Bierkandt et al. 2014; Wenz et al. 2014; Otto et al. 2016). The model describes the immediate response of the global economy to local disasters as well as its recovery dynamics in the disaster aftermath. Furthermore, price effects, which are important to assess the losses of large-scale disasters, can be analyzed. This renders the model well-suited for the assessment of the loss avalanches of unanticipated disasters. Acclimate can be also used to assess global adaptation options in future research.

Assume an unforeseen and abrupt production reduction by 10 % in the Japanese machinery sector. Figure 3.17 depicts the resulting cumulative consumption changes

as a function of time for Asia excluding Japan (gray dashed line) as well as for selected Asian economies. The production in the Japanese machinery sector is reduced for 20 days, which is highlighted by the gray shaded area. Since the Japanese economy is a major exporter of machinery products, reduced Japanese exports result in a global shortage of machinery, triggering price increases in the disaster aftermath. Higher prices reduce national consumption indicating losses in welfare. Asia's economy is strongly affected, due to the tight economic connections between Japan and most other Asian economies. Differences in consumption changes among the individual countries result from the different scarcities they perceive. The magnitude of the scarcities incurred crucially hinges on the dependence on Japan's machinery sector for supply and the capability of the affected production facilities to obtain the missing inputs from other suppliers. As these properties are of such importance, future extreme weather impacts on the Asian supply chains should ideally incorporate projections on the extreme weather events as well as on the developments of the trade network.

Figure 3.17: Global Consumption Changes



AFR = Africa, ASI = Asia, EU = European Union, FSU = former Soviet Union, LAM = Latin America, MEA = Middle East, NAM = North America.

Tracing consumption changes back to natural catastrophes (in other countries) that take effect through specific transmission channels is the subject of ongoing research. Studies of the 2011 Tohoku earthquake and tsunami provide some first attempts of quantification. It was shown that permanent energy supply problems led to a contraction of production and persisting supply shortages in Japan (Schnell and Weinstein 2012). As a consequence, consumption product availability decreased by 17% in Japan in the 2.5 weeks after the tsunami (Cavallo, Cavallo, and Rigobon 2014). Cavallo, Cavallo, and Rigobon (2014) report that prices of consumption were relatively sticky in the weeks following the tsunami. They conjecture that prices were largely kept stable to avoid consumer anger directly after the catastrophe and products out of stock are naturally not repriced. The study, however, finds price increases after some months at the time when stocks were replenished. These price increases reversed the deflation trend that existed before the earthquake. The authors find the same qualitative results for the 2010 earthquake in Chile. These statistical findings are to be incorporated into modeling methodology to improve quantitative projections for the future.

Factors Contributing to Supply Chain Vulnerability

There are a number of factors contributing to the vulnerability of an economy to extreme weather events. To reach maximum competitiveness, it was considered good practice to eliminate as many cost inefficiencies in production and along the supply chain as possible (Krafcik 1988; Wee and Wu 2009). With this goal in mind, several concepts have been developed. First, there is the practice of reducing the supplier base, which allows for quantity discounts and high quality assurance (Presutti 1992; Swift 1995; Treleven 1987). This comes with the drawback that failure of one of the suppliers might cut down production significantly. Moreover, redirecting demand to some new supplier might be costly or even impossible at short notice. Second, there is the concept of just-in-time production, which enables cost saving by reducing or even eliminating inventory holding (Golhar and Stamm 1991; Lee and Ebrahimpour 1984). Just as with the reduction of the supplier base, this measure increases the dependence on timely deliveries by the suppliers. Third, production has become increasingly fragmented—that is, production has been split into many stages outsourced to countries that allow for less cost-intensive production

(Holcomb and Hitt 2007; Quinn and Hilmer 1994). As a result of outsourcing and of the technological progress in transportation and communication, supply chains have been widely globalized: this globalization can certainly be considered one of the vehicles for many East Asian countries' economic development in the last decade. However, fragmentation and globalization increased the opaqueness of supply chains. Nowadays, supply chains are complex networks that render it difficult to monitor potential risks from the beginning of the production chain to one's own production facility (Goldin and Mariathan 2014).

Possible Adaptation Measures

The measures eliminating cost inefficiencies increase the risk of being incapable to counteract approaching supply shortages in a short time. Acknowledging this problem, experts argue that partially reversing some of the cost-saving processes, particularly the reduction of inventory holding and the reliance on a small supplier base (Sheffi and Rice 2005), would enhance the resilience of the global economy. Sharing information about potential bottlenecks with business partners might provide further insights for redesigning the trade connections (Wakolbinger and Cruz 2011). Experts also recommend making production more flexible allowing a greater substitutability of the inputs (Tang and Tomlin 2008; Sheffi and Rice 2005). Moreover, emergency plans that incorporate means to redirect demand to other suppliers at short notice are advocated (Tomlin 2006).

It is not clear whether the private sector's adaptation efforts increase the supply chain's stability and resilience sufficiently. Vague supply chain disruption risk assessments render it difficult to weigh the goal of becoming increasingly cost-efficient against being capable to respond to supply

chain disruptions. The opaqueness of the supply network and missing information on potential risks cause the risk assessments to be imprecise. Furthermore, the adoption of measures to increase responsiveness to supply chain disruptions might involve costs that many producers in developing countries cannot afford.

As repeated supply chain disruptions hamper economic growth, it is also in the public sector's interest to design a strategy that reduces supply chain vulnerability and to intervene if the private sector's adaptation efforts do not suffice. Several possible measures are suggested by the United States National Strategy for Global Supply Chain Security (Government of the United States 2012). The public sector can modernize and climate-proof important public supply chain infrastructure to prevent supply chain disruptions at the very outset. To promote climate-proofing of private production facilities, the public sector can support building projects serving as role models. It can give recommendations, run programs, set standards, or implement laws for specific building measures. To help firms in conducting supply chain risk assessments, the public sector can provide information on possible risks and enhance information-sharing practices. To support a fast and efficient recovery after a disruption, it can provide information about best practices. Regarding all efforts, collaboration with the private sector is advised to synchronize measures. As supply chain disruptions can spread across national borders, the public sector also should collaborate with foreign stakeholders and foreign policy makers playing important roles for supply chain operations. Thus, information sharing across borders can be enhanced. Furthermore, international collaboration facilitates the development and implementation of international standards, programs, and guidelines regarding stability and resilience of the global network.

References—Part 3

- Abid, M., et al. 2015. Farmers' Perceptions of Adaptation Strategies to Climate Change and their Determinants: The Case of Punjab Province, Pakistan. *Earth System Dynamics*. 6(1). pp. 225–243.
- Abid, M., et al. 2016. Climate Change Vulnerability, Adaptation and Risk Perceptions at Farm Level in Punjab, Pakistan. *Science of the Total Environment*. 547. pp. 447–460.
- Acemoglu, D., et al. 2012. The Network Origins of Aggregate Fluctuations. *Econometrica*. 80(5). pp. 1977–2016.
- Acemoglu, D., A. Ozdaglar, and N. Tahbaz-Salehi. 2014. *Microeconomic Origins of Macroeconomic Tail Risks*. NBER Working Paper No. 20865. Washington, DC.
- Adams, H., and W. N. Adger. 2013. The Contribution of Ecosystem Services to Place Utility as a Determinant of Migration Decision-Making. *Environment Research Letters*. 8(1).
- Adger, W. N., et al. 2015. Focus on Environmental Risks and Migration: Causes and Consequences. *Environmental Research Letters*. 10(6). 60201.
- Aerts, J., and W. Botzen. 2014. Adaptation: Cities' Response to Climate Risks. *Nature Climate Change*. 4. pp. 759–760.
- Aerts, J., et al. 2014. Evaluating Flood Resilience Strategies for Coastal Megacities. *Science*. 344(6183). pp. 1–3.
- Ahammad, R. 2011. Constraints of Pro-Poor Climate Change Adaptation in Chittagong City. *Environment and Urbanization*. 23(2). pp. 503–515.
- Ahmed, A., et al. 2012. *Where the Rain Falls" Project Case Study: Bangladesh. Results from Kurigram District, Rangpur Division*. London: CARE.
- Ashie, Y., and T. Kono. 2011. Urban-Scale CFD Analysis in Support of a Climate-Sensitive Design for the Tokyo Bay Area. *International Journal of Climatology*. 31(2). pp. 174–188.
- Asian Development Bank (ADB). 2009. *The Economics of Climate Change in Southeast Asia: A Regional Review*. Manila.
- . 2010. *Lighting the Future. Development Asia*. July–September. Manila.
- . 2011. *Accounting for Health Impacts of Climate Change*. Manila.
- . 2012. *Addressing Climate Change and Migration in Asia and the Pacific*. Manila.
- . 2013a. *Economics of Climate Change in East Asia*. Manila.
- . 2013b. *The Economics of Climate Change in the Pacific*. Manila.
- . 2014. *Assessing the Costs of Climate Change and Adaptation in South Asia*. Manila.
- Asis, M. M. B. 2006. *How International Migration Can Support Development: A Challenge for the Philippines*. Manila: Scalabrini Migration Center–Philippines.
- Atta-ur-Rehman, K., et al. 2013. *Desk Study: Indus Floods Research Project*. Boulder: The Institute for Social and Environmental Transition.
- Baccini, M., et al. 2008. Heat Effects on Mortality in 15 European Cities. *Epidemiology*. 19(5). pp. 711–719.
- Ballester, J., et al. 2011. Long-Term Projections and Acclimatization Scenarios of Temperature-Related Mortality in Europe. *National Communications*. 2. p. 358.
- Bandara, J. S., and Y. Cai. 2014. The Impact of Climate Change on Food Crop Productivity, Food Prices and Food Security in South Asia. *Economic Analysis and Policy*. 44(4). pp. 451–465.
- Bangladesh Bureau of Statistics. 2015. *Population Density and Vulnerability: A Challenge for Sustainable Development of Bangladesh*. Dhaka: Bangladesh Bureau of Statistics.
- Bardsley, D. K., and G. J. Hugo. 2010. Migration and Climate Change: Examining Thresholds of Change to Guide Effective Adaptation Decision-Making. *Population and Environment*. 32(2–3). pp. 238–262.
- Barragán, J. M., and M. de Andrés. 2015. Analysis and Trends of the World's Coastal Cities and Agglomerations. *Ocean Coastal Management*. 114. pp. 11–20.
- Barnett, J., and W. N. Adger. 2007. Climate Change, Human Security and Violent Conflict. *Political Geography*. 26(6). pp. 639–655.
- Beisheim, M. 2013. *Der »Nexus« Wasser-Energie-Nahrung*. Berlin: Deutsches Institut für Internationale Politik und Sicherheit. In German.
- Bernauer, T., and T. Siegfried. 2012. Climate Change and International Water Conflict in Central Asia. *Journal of Peace Research*. 49(1). pp. 227–239.
- Bierkandt, R., et al. 2014. Acclimate – An Economic Damage Propagation Model. Part 1: Basic Formulation of Damage Transfer within a Global Supply Network

- and Damage Conserving Dynamics. *Environment Systems and Decisions*. 34(1). pp. 507–524.
- Bhatt, S., et al. 2013. The Global Distribution and Burden of Dengue. *Nature*. 496(7446). pp. 504–507.
- Bhattacharyya, A., and M. Werz. 2012. *Climate Change, Migration, and Conflict in South Asia. Rising Tensions and Policy Options across the Subcontinent*. Washington, DC: Center for American Progress.
- Biermann, F., and I. Boas. 2009. Protecting Climate Refugees: The Case for a Global Protocol. *Current*. (509). pp. 21–26.
- Biswas, A. K. 2012. Impacts of Large Dams: Issues, Opportunities and Constraints. In C. Tortajada, D. Altinbilek, and A. K. Biswas. eds. *Impacts of Large Dams: A Global Assessment*. Berlin: Springer-Verlag.
- Black, R., W. Adger, and N. Arnell. 2011. The Effect of Environmental Change on Human Migration. *Global Environmental Change*. 21. pp. S3–S11.
- Black, R., et al. 2011. Migration as Adaptation. *Nature*. 478. pp. 447–449.
- Black, R. E., et al. 2013. Maternal and Child Undernutrition and Overweight in Low-Income and Middle-Income Countries. *Lancet*. 382(9890). pp. 427–451.
- Blondel, A. 2012. *Climate Change Fuelling Resource-Based Conflicts in the Asia-Pacific*. New York: United Nations Development Programme.
- Boettle, M., D. Rybski, and J. P. Kropp. 2016. Quantifying the Effect of Sea Level Rise and Flood Defence: A Point Process Perspective on Coastal Flood Damage. *Natural Hazards and Earth System Sciences*. 16(2). pp. 559–576.
- Bohra-Mishra, P., M. Oppenheimer, and S. M. Hsiang. 2014. Nonlinear Permanent Migration Response to Climatic Variations but Minimal Response to Disasters. *Proceedings of the National Academy of Sciences*. 111(27). pp. 9780–9785.
- Bordey, F. H., et al. 2013. *Rice Yield and Migration: The Philippine Experience*. Los Banos, Philippines: Economy and Environment Program for Southeast Asia.
- Brander, L., and F. Eppink. 2015. *The Economics of Ecosystems and Biodiversity for Southeast Asia*. Los Banos: ASEAN TEEB.
- Brown, S., S. Hanson, and R. J. Nicholls. 2013. Implications of Sea-Level Rise and Extreme Events Around Europe: A Review of Coastal Energy Infrastructure. *Climatic Change*. 122(1). pp. 81–95.
- Bruno, J. F., and E. R. Selig. 2007. Regional Decline of Coral Cover in the Indo-Pacific: Timing, Extent, and Subregional Comparisons. *PLoS One*. 2(8). p. e711.
- Brzoska, M., and C. Fröhlich. 2015. Climate Change, Migration and Violent Conflict: Vulnerabilities, Pathways and Adaptation Strategies. *Migration and Development*. pp. 1–21.
- Brzoska, M., and A. Oels. 2012. Massenmigration und Klimakriege? Klimawandel als Sicherheitsbedrohung. *Wiss. Frieden*. (3). pp. 19–22. In German.
- Buhaug, H. 2015. Climate-Conflict Research: Some Reflections on the Way Forward. *Wiley Interdisciplinary Reviews: Climate Change*. 6(3). pp. 269–275.
- Buhaug, H., N. P. Gleditsch, and O. M. Theisen. 2008. *Implications of Climate Change for Armed Conflict*. Washington, DC: World Bank.
- Buhaug, H., et al. 2014. One Effect to Rule Them All? A Comment on Climate and Conflict. *Climatic Change*. 127(3–4). pp. 391–397.
- Burke, L., L. Selig, and M. Spalding. 2002. *Reefs at Risk in Southeast Asia*. Washington, DC: World Resources Institute.
- Burke, L., et al. 2011. *Reefs at Risk Revisited*. Washington, DC: World Resources Institute.
- Burke, M., S. M. Hsiang, and E. Miguel. 2015. Global Non-linear Effect of Temperature on Economic Production. *Nature*. (1). pp. 1–16.
- Butler, C. D. 2009. Food Security in the Asia-Pacific: Malthus, Limits and Environmental Challenges. *Asia Pacific Journal of Clinical Nutrition*. 18(4). pp. 577–584.
- Cai, R., et al. 2016. Climate Variability and International Migration: The Importance of the Agricultural Linkage. *Journal of Environmental Economics and Management*. 79. pp. 135–151.
- Caminade, C., et al. 2014. Impact of Climate Change on Global Malaria Distribution. *Proceedings of the National Academy of Sciences*. 111(9). pp. 3286–3291.
- Campbell, J. R. 2010. Climate Change and Population Movement in Pacific Island Countries. *Climatic Change*. pp. 29–50.
- . 2014. Climate-Change Migration in the Pacific. *Contemporary Pacific*. 26(1). pp. 1–28.
- Carilli, J., et al. 2012. Historical Temperature Variability Affects Coral Response to Heat Stress. *PLoS One*. 7(3). p. e34418.
- Carius, A., D. Tänzler, and J. Winterstein. 2006. *Weltkarte von Umweltkonflikten – Ansätze zur Typologisierung*. Berlin: WBGU (in German).
- Cattaneo, C., and G. Peri. 2015. The Migration Response to Increasing Temperatures. *Journal of Development Economics*. 122. pp. 127–146

- Cavallo, A., E. Cavallo, and R. Rigobon. 2014. Prices and Supply Disruptions during Natural Disasters. *Review of Income and Wealth*. 2. 60(S2). pp. S449–S471.
- Christopher, M., and H. Peck. 2004. Building the Resilient Supply Chain. *The International Journal of Logistics Management*. 15(2). pp. 564–578.
- Challinor, A. J., and T. R. Wheeler. 2008. Crop Yield Reduction in the Tropics under Climate Change: Processes and Uncertainties. *Agricultural and Forest Meteorology*. 148(3). pp. 343–356.
- Chapman, I. 2014. The End of Peak Oil? Why This Topic Is Still Relevant Despite Recent Denials. *Energy Policy*. 64. pp. 93–101.
- Chatterjee, R., et al. 2016. Urban Food Security in Asia: a Growing Threat. In R. Shaw et al., eds. *Urban Disasters and Resilience in Asia*. Oxford: Elsevier.
- Chaudhry, P., and G. Ruyschaert. 2007. *Climate Change and Human Development in Viet Nam*. Geneva: Human Development Report Office.
- Checkley, W., et al. 2000. Effects of El Niño and Ambient Temperature on Hospital Admissions for Diarrhoeal Diseases in Peruvian Children. *Lancet*. 355(9202). pp. 442–450.
- Chen, F., et al. 2012. Reconstructed Temperature for Yong'an, Fujian, Southeast China: Linkages to the Pacific Ocean Climate Variability. *Global Planetary Change*. 86–87. pp. 11–19.
- Chung, Y., et al. 2015. Mortality Related to Extreme Temperature for 15 Cities in Northeast Asia. *Epidemiology*. 26(2). pp. 255–262.
- Church, J. A., and N. J. White. 2011. Sea-Level Rise from the Late 19th to the Early 21st Century. *Surveys in Geophysics*. 32(4–5). pp. 585–602.
- Clark, W. A. V. 2007. *Environmentally Induced Migration and Conflict*. Berlin. Wissenschaftlicher Beirat der Bundesregierung Glob. Umweltveränderung.
- Cooley, H., et al. 2009. *Understanding and Reducing the Risks of Climate Change for Transboundary Waters*. Oakland, California: Pacific Institute.
- Costa, L., V. Tekken, and J. Kropp. 2009. Threat of Sea Level Rise: Costs and Benefits of Adaptation in European Union Coastal Countries. *Journal of Coastal Research*. 56(56). pp. 223–227.
- Costa, M. M., K. Schwerdtner, and S.H. Paragay. 2013. Adaptation Under Changing Urban Patterns: The Climatic Perspective of Migration. In K. Ruppel et al. [eds]. *Climate Change: International Law and Global Governance. Volume 2: Policy, Diplomacy and Governance in a Changing Environment*. Baden-Baden. Ruppel-Schiliching. pp. 785–798.
- Crank, J. P., and L. S. Jacoby. 2015. *Crime, Violence, and Global Warming*. London: Routledge.
- Cui, L., and J. Shi. 2012. Urbanization and Its Environmental Effects in Shanghai, China. *Urban Climate*. 2. pp. 1–15.
- Cullen, H. M., et al. 2000. Climate Change and the Collapse of the Akkadian Empire: Evidence from the Deep Sea. *Geology*. 28(4). pp. 379–382.
- Dai, A. 2011. Drought under Global Warming: A Review. *Wiley Interdisciplinary Reviews: Climate Change*. 2(1). pp. 45–65.
- Dankers, R., et al. 2013. First Look at Changes in Flood Hazard in the Inter-Sectoral Impact Model Intercomparison Project Ensemble. *Proceedings of the National Academy of Sciences*. pp. 1–5.
- Dasgupta, S., et al. 2009. The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis. *Climatic Change*. 93(3–4). pp. 379–388.
- Dasgupta, S., et al. 2010. *Vulnerability of Bangladesh to Cyclones in a Changing Climate. Potential Damages and Adaptation Cost*. Washington, DC: World Bank.
- David, M., and A. Pandya. 2009. *Troubled Waters: Climate Change, Hydropolitics, and Transboundary Resources*. Washington, DC. Global Policy Forum.
- Davletkeldiev, A., et al. 2009. *The Kyrgyz Republic's Second National Communication to the United Nations Framework Convention on Climate Change*. Bishkek: United Nations Development Programme and the State Agency for the Environment Protection and Forestry under the Government of the Kyrgyz Republic.
- Delcan Corporation. 2012. *Cost of Adaptation, Sea Dikes & Alternative Strategies: Final Report*. Victoria, British Columbia: Ministry of Forests, Lands and Natural Resource Operations.
- Di Liberto, T. 2016. India Heat Wave Kills Thousands. *Climate Watch*. pp. 9–13.
- Dodman, D., and D. Satterthwaite. 2008. Institutional Capacity, Climate Change Adaptation and the Urban Poor. *IDS Bulletin*. 39(4). pp. 67–74.
- Donges, J. F., et al. 2015. Non-linear Regime Shifts in Holocene Asian Monsoon Variability: Potential Impacts on Cultural Change and Migratory Patterns. *Climate of the Past*. 11(5). pp. 709–741.
- D'Ooge, C. 2008. Queer Katrina: Gender and Sexual Orientation Matters in the Aftermath of the Disaster. In B. Willinger [ed.]. *Katrina and the Women of New*

- Orleans. Tulane: Newcomb College Center for Research on Women. pp. 22–24.
- Döös, B. R. 1997. Can Large-Scale Environmental Migrations Be Predicted? *Global Environmental Change*. 7(1). pp. 41–61.
- Dossou, K. M. R., and B. Glehouenou-Dossou. 2007. The Vulnerability to Climate Change of Cotonou (Benin): The Rise in Sea Level. *Environment and Urbanization*. 19(1). pp. 65–79.
- Draper, S. E., and J. E. Kundell. 2007. Impact of Climate Change on Transboundary Water Sharing. *Journal of Water Resources Planning and Management*. 133(5). 405–415.
- Drysdale, R., et al. 2006. Late Holocene Drought Responsible for the Collapse of Old World Civilizations Is Recorded in an Italian Cave Flowstone. *Geology*. 34(2). pp. 101–104.
- Dun, O. 2011. Migration and Displacement Triggered by Floods in the Mekong Delta. *International Migration*. 49(SUPPL.1).
- Ebi, K. L., and D. Mills. 2013. Winter Mortality in a Warming Climate: A Reassessment. *Wiley Interdisciplinary Reviews: Climate Change*. 4(3). pp. 203–212.
- Ebinger, C. K. 2011. *Energy and Security in South Asia: Cooperation or Conflict?* Washington, DC: Brookings Institution Press.
- The Economist. 2012. *Counting the Cost of Calamities*. 14 January.
- Elderfield, H., et al. 2005. *Ocean Acidification due to Increasing Atmospheric Carbon Dioxide*. London: The Royal Society.
- Enarson, E., A. Fothergill, and L. Peek. 2007. Gender and Disaster: Foundations and Directions. In R. Havidan, E.L. Quarantelli, and R.R. Dynes, eds. *Handbook of Disaster Research*. pp. 130–146. New York: Springer.
- Faist, T. 2001. *The Volume and Dynamics of International Migration and Transnational Social Spaces*. Oxford Scholarship Online.
- Fay, M., R. I. Block, and J. Ebinger. 2010. *Adapting to Climate Change in Eastern Europe and Central Asia*. Washington, DC: World Bank.
- Food and Agriculture Organization of the United Nations (FAO). 2016. *AQUASTAT Main Database*. Rome.
- Frieler, K., et al. 2012. Limiting Global Warming to 2°C Is Unlikely to Save Most Coral Reefs. *Nature Climate Change*. 2(9). pp. 1–6.
- Fröhlich, C., and G. Gioli. 2015. Gender, Conflict, and Global Environmental Change. *Peace Review*. 27(2). pp. 137–146.
- Gabaix, X. 2011. The Granular Origins of Aggregate Fluctuations. *Econometrica*. 79(3). pp. 733–772.
- Gamper, C. D., M. Thoni, and H. Weck-Hannemann. 2006. A Conceptual Approach to the Use of Cost Benefit and Multi Criteria Analysis in Natural Hazard Management. *Natural Hazards and Earth System Sciences*. 6(2). pp. 293–302.
- Garg, A., P. Naswa, and P. R. Shukla. 2015. Energy Infrastructure in India: Profile and Risks under Climate Change. *Energy Policy*. 81. pp. 226–238.
- Gasparrini, A., and B. Armstrong. 2010. Time Series Analysis on the Health Effects of Temperature: Advancements and Limitations. *Environmental Research*. 110(6). pp. 633–638.
- . 2012. The Impact of Heat Waves on Mortality. *Epidemiology*. 22(1). pp. 68–73.
- Gasparrini, A., et al. 2015. Mortality Risk Attributable to High and Low Ambient Temperature: A Multicountry Observational Study. *Lancet*. 386(9991). pp. 369–375.
- Gething, P. W., et al. 2010. Climate Change and the Global Malaria Recession. *Nature*. 465(7296). pp. 342–345.
- Giese, E., and J. Sehring. 2007. *Regional Expertise – Destabilisierungs- und Konfliktpotenzial prognostizierter Umweltveränderung in der Region Zentralasien 2020/2050*. Berlin. WBGU. In German.
- Ginnetti, J., and T. Franck. 2014. *Assessing Drought-Induced Displacement*. Geneva: Internal Displacement Monitoring Centre.
- Glanemann, N., et al. 2016. *Abrupt Events and the Global Supply Network: A Novel Measure for Cascading Production Losses*. Potsdam: Potsdam Institute for Climate Impact Research.
- Goldin, I., and M. Mariathan. 2014. *The Butterfly Defect: How Globalization Creates Systemic Risks, and What to Do About It*. Princeton, NJ: Princeton University Press.
- Goldstone, J. A. 2002. Population and Security: How Demographic Change Can Lead to Violent Conflict. *Journal of International Affairs*. 56(1). pp. 3–21.
- Golhar, D. Y., and C. L. Stamm. 1991. The Just-in-Time Philosophy: A Literature Review. *International Journal of Production Research*. 29(4). pp. 657–676.
- Goreau, T. J., and R. L. Hayes. 1994. Coral Bleaching and Ocean “Hot Spots”. *Ambio*. 23. pp. 176–180.
- Government of India, Ministry of Environment and Forest. 2012. *India Second National Communication to the United Nations Framework Convention on Climate Change*. New Delhi: United Nations Development Programme.

- Government of the United States, White House. 2012. *National Strategy for Global Supply Chain Security*. Washington, DC.
- Government of Uzbekistan. Main Administration of Hydrometeorology. 2009. *Second National Communication of the Republic of Uzbekistan under the United Nations Framework Convention on Climate Change*. Tashkent: Centre of Hydrometeorological Service under the Cabinet of Ministers of the Republic of Uzbekistan.
- Government of Viet Nam, Ministry of Natural Resources and the Environment (MoNRE). 2010. *Climate Change in the Mekong Delta: Climate Scenarios, Sea Level Rise, Other Effects*. Ho Chi Minh City.
- Green, T. R., et al. 2011. Beneath the Surface of Global Change: Impacts of Climate Change on Groundwater. *Journal of Hydrology*. 405(3–4). pp. 532–560.
- Gubler, D. J., et al. 2001. Climate Variability and Change in the United States: Potential Impacts on Vector- and Rodent-Borne Diseases. *Environmental Health Perspectives*. 109(Suppl. 2). pp. 223–233.
- Gupta, H., S. Kao, and M. Dai. 2012. The Role of Mega Dams in Reducing Sediment Fluxes: A Case Study of Large Asian Rivers. *Journal of Hydrology*. 464–465. pp. 447–458.
- Haigh, I. D., et al. 2011. Regional Changes in Mean Sea Level Around Western Australia Between 1897 and 2008. In *Coasts and Ports 2011: Diverse and Developing*. Proceedings of the 20th Australasian Coastal and Ocean Engineering Conference and the 13th Australasian Port and Harbour Conference, pp. 280–285. Barton: Sydney.
- Hales, S., et al. 2002. Potential Effect of Population and Climate Changes on Global Distribution of Dengue Fever: An Empirical Model. *Lancet*. 360(9336). pp. 830–834.
- Hallegatte, S., F. Henriot, and J. Corfee-Morlot. 2010. The Economics of Climate Change Impacts and Policy Benefits at City Scale: A Conceptual Framework. *Climatic Change*. 104. pp. 51–87.
- Hallegatte, S., et al. 2013. Future Flood Losses in Major Coastal Cities. *Nature Climate Change*. 3(9). pp. 802–806.
- Hanjra, M., and M. E. Qureshi. 2010. Global Water Crisis and Future Food Security in an Era of Climate Change. *Food Policy*. 35(5). pp. 365–377.
- Hassani-Mahmooei, B., and B. W. Parris. 2012. Climate Change and Internal Migration Patterns in Bangladesh: An Agent-Based Model. *Environment and Development Economics*. 17(6). pp. 763–780.
- Harkey, J., et al. 2014. *Challenges of Addressing Disaster-Induced Urban Displacement in the Philippines*. Oslo: Norwegian Refugee Council.
- Hatton, T. J. 2005. Explaining Trends in UK immigration. *Journal of Population Economics*. 18(4). pp. 719–740.
- Herberg, M. E. 2004. Energy: Asia's Energy Insecurity—Cooperation or Conflict? In A. J. Tellis and M. Wills [eds]. *Strategic Asia 2004–05: Confronting Terrorism in the Pursuit of Power*. Washington, DC: The National Bureau of Asian Research.
- Hijioka, Y. et al. 2014. Regional Aspects. Chapter 24 – Asia. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press.
- Hilmi, N., et al. 2015. *Bridging the Gap between Ocean Acidification Impacts and Economic Valuation: Regional Impacts of Ocean Acidification on Fisheries and Aquaculture*. Gland: International Union for Conservation of Nature (IUCN).
- Hinkel, J., and R. J. T. Klein. 2009. Integrating Knowledge to Assess Coastal Vulnerability to Sea-Level Rise: The Development of the DIVA Tool. *Global Environmental Change*. 19(3). pp. 384–395.
- Hinkel, J., et al. 2014. Coastal Flood Damage and Adaptation Costs Under 21st Century Sea-Level Rise. *Proceedings of the National Academy of Sciences*. 111(9). pp. 3292–7.
- Hoegh-Guldberg, O. 2014. Coral Reefs in the Anthropocene: Persistence or the End of the Line? *Geological Society*. London. Special Publications. 395(1). pp. 167–183.
- Hoegh-Guldberg, O., et al. 2009. *The Coral Triangle and Climate Change: Ecosystems, People and Societies at Risk*. Brisbane: WWF Australia.
- Holcomb, T. R., and M. A. Hitt. 2007. Toward a Model of Strategic Outsourcing. *Journal of Operations Management*. 25(2). pp. 464–481.
- Honda, Y., et al. 2014. Heat-Related Mortality Risk Model for Climate Change Impact Projection. *Environmental Health and Preventive Medicine*. 19(1). pp. 56–63.
- Hoque Mollah, T., and J. Ferdaush. 2015. Riverbank Erosion, Population Migration and Rural Vulnerability

- in Bangladesh. *Environment and Ecology Research*. 3(5). pp. 125–131.
- Hugo, G. 2011. Future Demographic Change and Its Interactions with Migration and Climate Change. *Global Environmental Change*. 21. pp. S21–S33.
- Huizinga, H. J. 2007. *Flood Damage Functions for EU Member States*. HKV Consultants. Technical report implemented in the framework of the contract # 382441-F1SC awarded by the European Commission Joint Research Centre.
- Hunt, A., and P. Watkiss. 2011. Climate Change Impacts and Adaptation in Cities: A Review of the Literature. *Climatic Change*. 104(1). pp. 13–49.
- Hunter, L. M. and E. David. 2009. *Climate Change and Migration: Considering Gender Dimensions*. Boulder: Institute of Behavioral Science.
- Huq, S., and H. Reid. 2007. *A Vital Approach to the Threat Climate Change Poses to the Poor. Community-Based Adaptation: An IIED Briefing*. London: International Institute for Environment and Development.
- Ide, T. K. 2014. *Towards Methodological Pluralism: An Empirical Evaluation of Research Methods for Assessing the Link between Climate Change and Violent Conflict*. Hamburg: Hamburg University.
- Immerzeel, W. W., L. P. H. van Beek, and M. F. P. Bierkens. 2010. Climate Change Will Affect the Asian Water Towers. *Science*. 328(5984). pp. 1382–1385.
- Internal Displacement Monitoring Centre (IDMC). 2012. *Global Estimates 2015: People Displaced by Natural Hazard-Induced Disasters*. Geneva: Internal Displacement Monitoring Centre.
- . 2015. Philippines: Long-Term Recovery Challenges Remain in the Wake of Massive Displacement. Geneva: Internal Displacement Monitoring Centre.
- Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, NY: Cambridge University Press.
- Islam, M. R., and M. Hasan. 2016. Climate-Induced Human Displacement: A Case Study of Cyclone Aila in the South-West Coastal Region of Bangladesh. *Natural Hazards*. 81(2). pp. 1051–1071.
- Jiang, L., and B. C. O'Neill. 2017. Global Urbanization Projections for the Shared Socioeconomic Pathways. *Global Environmental Change*. 42. pp. 193–199
- Kälin, W. 2010. Conceptualising Climate-Induced Displacement. In J. McAdam, eds. *Climate Change and Displacement: Multidisciplinary Perspectives*. Oxford: Hart Publishing.
- Karnauskas, K. B., J. P. Donnelly, and K. J. Anchukaitis. 2016. Future Freshwater Stress for Island Populations. *Nature Climate Change*. 6. pp. 720–725.
- Kataoka, K., et al. 2009. Urban Warming Trends in Several Large Asian Cities Over the Last 100 Years. *Science of the Total Environment*. 407(9). pp. 3112–3119.
- Kelley, C. P., et al. 2015. Climate Change in the Fertile Crescent and Implications of the Recent Syrian Drought. *Proceedings of the National Academy of Sciences*. 112(11). pp. 3241–3246.
- Kennett, D. J., et al. 2012. Development and Disintegration of Maya Political Systems in Response to Climate Change. *Science*. 338(6108). pp. 788–791.
- Kerschner, C., et al. 2013. Economic Vulnerability to Peak Oil. *Global Environmental Change*. 23(6). pp. 1424–1433.
- Khan, M. A., et al. 2016. The Challenge of Climate Change and Policy Response in Pakistan. *Environmental Earth Sciences*. 75(5). pp. 412.
- Kim, Y. H., and J. J. Baik. 2004. Daily Maximum Urban Heat Island Intensity in Large Cities of Korea. *Theoretical and Applied Climatology*. 79(3–4). pp. 151–164.
- Kinney, P. L., et al. 2015. Winter Season Mortality: Will Climate Warming Bring Benefits? *Environmental Research Letters*. 10(6). p. 64016. doi:10.1088/1748-9326/10/6/064016
- Kjellstrom, T., B. Lemke, and M. Otto. 2013. Mapping Occupational Heat Exposure and Effects in South-East Asia: Ongoing Time Trends 1980–2011 and Future Estimates to 2050. *Industrial Health*. 51(1). pp. 56–67.
- Kniveton, D. R., C. Smith, and S. Wood. 2011. Agent-Based Model Simulations of Future Changes in Migration Flows for Burkina Faso. *Global Environmental Change*. 21. pp. S34–S40.
- Kniveton, D. R., C. D. Smith, and R. Black. 2012. Emerging Migration Flows in a Changing Climate in Dryland Africa. *Nature Climate Change*. 2(6). pp. 444–447.
- Knox, J., et al. 2012. Climate Change Impacts on Crop Productivity in Africa and South Asia. *Environmental Research Letters*. 7.
- Knutson, T. R. et al. 2010. Tropical Cyclones and Climate Change. *Nature Geoscience*. 3. pp. 157–163.
- Komar, P. D., and J.C. Allan. 2008. Increasing Hurricane-Generated Wave Heights along the U.S. East Coast and Their Climate Controls. *Journal of Coastal Resources*. 242. pp. 479–488.

- Krafcik, J. F. 1988. Triumph of The Lean Production System. *Sloan Management Review*. 30(1). pp. 41–52.
- Kreft, S., et al. 2015. *Global Climate Risk Index 2013: Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2013 and 1994 to 2013*. Bonn:Germanwatch.
- Kroeker, K. J., et al. 2013. Impacts of Ocean Acidification on Marine Organisms: Quantifying Sensitivities and Interaction with Warming. *Global Change Biology*. 19(6). pp. 1884–1896.
- Kumar, S. N., et al. 2014. Vulnerability of Wheat Production to Climate Change in India. *Climate Research*. 59. pp. 173–187.
- Lal, M. 2011. Implications of Climate Change in Sustained Agricultural Productivity in South Asia. *Regional Environmental Change*. 11(S1). pp. 79–94.
- Lavell, C., and J. Ginnetti. 2014. *The Risk of Disaster-Induced Displacement in South-East Asia and China*. Technical paper. Geneva: Internal Displacement Monitoring Centre.
- Le Quere, C., et al. 2012. The Global Carbon Budget 1959–2011. *Earth System Science Data*. 5. pp. 1107–1157.
- Le, T. V. H., et al. 2007. The Combined Impact on the Flooding in Vietnam's Mekong River Delta of Local Man-Made Structures, Sea Level Rise, and Dams Upstream in the River Catchment. *Estuarine, Coastal and Shelf Science*. 71(1–2). pp. 110–116.
- Lee, H. L. 2004. The Triple-A Supply Chain. *Harvard Business Review*. 82(10). pp. 102–120.
- Lee, S. M., and M. Ebrahimpour. 1984. Just-in-Time Production System: Some Requirements for Implementation. *International Journal of Operations and Production Management*. 4(4). pp. 3–15.
- Lehner, B., et al. 2011. *Global Reservoir and Dam (GRanD) database*. Palisades, New York: NASA Socioeconomic Data and Applications Center (SEDAC).
- Levermann, A. 2014. Make Supply Chains Climate-Smart. *Nature*. 504. pp. 27–29.
- Lewis, J. I. 2009. Climate Change and Security: Examining China's Challenges in a Warming World. *International Affairs*. 85(6). pp. 1195–1213.
- Lioubimtseva, E., and G. M. Henebry. 2009. Climate and Environmental Change in arid Central Asia: Impacts, Vulnerability, and Adaptations. *Journal of Arid Environments*. 73(11). pp. 963–977.
- Liu, W., et al. 2007. Temporal Characteristics of the Beijing Urban Heat Island. *Theoretical and Applied Climatology*. 87(1–4). pp. 213–221.
- Liu, L., et al. 2014. Global, Regional, and National Causes of Child Mortality in 2000–13, with Projections to Inform Post-2015 Priorities: An Updated Systematic Analysis. *Lancet*. 385(9966). pp. 430–440.
- Liu, B., et al. 2016. Similar Estimates of Temperature Impacts on Global Wheat Yield by Three Independent Methods. *Nature Climate Change*. 6. pp. 1130–1136.
- Lloyd, S. J., R. S. Kovats, and B. G. Armstrong. 2007. Global Diarrhoea Morbidity, Weather and Climate. *Climate Research*. 34(2). pp. 119–127.
- Lloyd, S. J., R. S. Kovats, and Z. Chalabi. 2011. Climate Change, Crop Yields, and Undernutrition: Development of a Model to Quantify the Impact of Climate Scenarios on Child Undernutrition. *Environmental Health Perspectives*. 119(12). pp. 1817–1824.
- Locke, J. T. 2009. Climate Change-Induced Migration in the Pacific Region: Sudden Crisis and Long-Term Developments. *Geography Journal*. 175(3). pp. 171–180.
- Lough, J. M. 2012. Small Change, Big Difference: Sea Surface Temperature Distributions for Tropical Coral Reef Ecosystems, 1950–2011. *Journal of Geophysical Research: Oceans*. 117(C9). p. C09018.
- Lum, T., and R. Margesson. 2014. Typhoon Haiyan (Yolanda): U.S. and International Response To Philippines Disaster. *Current Politics and Economics of South, Southeastern, and Central Asia*. 23(2). pp. 209–246.
- Lutz, W. 2010. *Emerging Population Issues in Eastern Europe and Central Asia: Research Gaps on Demographic Trends, Human Capital and Climate Change, Eastern Europe and Central Asia Regional*. New York, NY: United Nations Population Fund.
- Ly, Z. F., et al. 2013. Climate Change Impacts on Regional Winter Wheat Production in Main Wheat Productions Regions of China. *Agriculture and Forest Meteorology*. 171. pp. 234–248.
- Mallah, H. B. 2013. *Social Inequality and Environmental Threats in Indus Delta Villages: Pakistan*. Bremen: Center on Migration, Citizenship and Development.
- Margat, J., K. Frenken, and J.-M. Faurès. 2005. *Key Water Resources Statistics in AQUASTAT: FAO's Global Information System on Water and Agriculture*. International Work Session on Water Statistics. Vienna.
- Masumoto, K. 2006. Characteristics of Air Temperature Distribution in 2005 and Situation of Heat Island in Osaka City. *Journal of Heat Island Institute International*. 1. pp. 30–35.

- Mat, N., et al. 2014. Socio-ecological Transitions toward Low-Carbon Port Cities: Trends, Changes and Adaptation Processes in Asia and Europe. *Journal of Cleaner Production*. 114. pp. 362–375.
- Matthews, T. K. R., R. L. Wilby, and C. Murphy. 2017. Communicating the Deadly Consequences of Global Warming for Human Heat Stress. *Proceedings of the National Academy of Sciences*. PNAS early edition.
- Mayda, A. M. 2009. International Migration: A Panel Data Analysis of the Determinants of Bilateral Flows. *Journal of Population and Economics*. 23(4). pp. 1249–1274.
- McEvoy, D. 2007. Climate Change and Cities. *Built Environment*. 33, pp. 4–9.
- McGranahan, G., D. Balk, and B. Anderson. 2007. The Rising Tide: Assessing the Risks of Climate Change and Human Settlements in Low Elevation Coastal Zones. *Environment and Urbanization*. 19(1). pp. 17–37.
- McLeman, R., and B. Smit. 2006. Migration as an Adaptation to Climate Change. *Climatic Change*. 76(1–2). pp. 31–53.
- McLeod, E., et al. 2010. Sea-Level Rise Vulnerability in the Countries of the Coral Triangle. *Sustainability Science*. 5(2). pp. 207–222.
- McMichael, A. J., R. E. Woodruff, and S. Hales. 2006. Climate Change and Human Health: Present and Future Risks. *Lancet*. 367(9513). pp. 859–869.
- Mearns, R., and A. Norton, eds. 2010. *Social Dimensions of Climate Change*. Washington, DC: World Bank.
- Meissner, K. J., T. Lippmann, and S. Gupta. 2012. Large-Scale Stress Factors Affecting Coral Reefs: Open Ocean Sea Surface Temperature and Surface Seawater Aragonite Saturation over the Next 400 Years. *Coral Reefs*. 31(2). pp. 309–319.
- Merz, B., et al. 2010. Review Article: Assessment of Economic Flood Damage. *Natural Hazards and Earth System Sciences*. 10(8). pp. 1697–1724.
- Meyers, W. H., et al. 2012. *Issues Affecting the Future of Agriculture and Food Security for Europe and Central Asia*. Food and Agriculture Organization of the United Nations. Regional Office for Europe and Central Asia. Budapest: FAO.
- Miao, S., et al. 2009. An Observational and Modeling Study of Characteristics of Urban Heat Island and Boundary Layer Structures in Beijing. *Journal of Applied Meteorology and Climatology*. 48(3). pp. 484–501.
- Milne, G. A., A. J. Long, and S. E. Bassett. 2005. Modelling Holocene Relative Sea-Level Observations from the Caribbean and South America. *Quaternary Science Reviews*. 24(10–11). pp. 1183–1202.
- Miyan, M. A. 2015. Droughts in Asian Least Developed Countries: Vulnerability and Sustainability. *Weather Climate Extremes*. 7. pp. 8–23.
- Mortreux, C., and J. Barnett. 2009. Climate Change, Migration and Adaptation in Funafuti, Tuvalu. *Global Environmental Change*. 19(1). pp.105–112.
- Mudersbach, C., and J. Jensen. 2010. Nonstationary Extreme Value Analysis of Annual Maximum Water Levels for Designing Coastal Structures on the German North Sea Coastline. *Journal of Flood Risk Management*. 3(1). pp. 52–62.
- Mueller, V., C. Gray, and K. Kosec. 2014. Heat Stress Increases Long-Term Human Migration in Rural Pakistan. *Nature Climate Change*. 4(3). pp. 182–185.
- Murakami, A., et al. 2005. Trends in Urbanization and Patterns of Land Use in the Asian Mega Cities Jakarta, Bangkok, and Metro Manila. *Landscape and Urban Planning*. 70. pp. 251–259.
- Myers, N. 2002. Environmental Refugees: a Growing Phenomenon of the 21st Century. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*. 357(1420). pp. 609–13.
- Nansen Initiative Southeast Asian Regional Consultation. 2014. *Background Paper: Human Mobility in the Context of Disasters and Climate Change in Southeast Asia*. Geneva: The Nansen Initiative.
- Naser, M. M. 2011. Climate Change, Environmental Degradation, and Migration: A Complex Nexus, *William & Mary Environmental Law and Policy Review*. 36(3). pp. 712–768.
- Nelson, G. C., et al. 2009. *Climate Change. Impact on Agriculture and Costs of Adaptation*. Washington DC: International Food Policy Research Institute.
- Nelson, G. C., et al. 2010a. *Food Security and Climate Change*. IFPRI Issue Brief 66. Washington DC: International Food Policy Research Institute.
- Nelson, G.C., et al. 2010b. *The Costs of Agricultural Adaptation to Climate Change*. World Bank. Washington, D.C.: World Bank.
- Nicholls, R., et al. 2010. *Economics of Coastal Zone Adaptation to Climate Change*. World Bank Discussion Papers No. 10. Washington, DC: World Bank.
- Nicholls, R. J. 2007. *Adaptation Options for Coastal Areas and Infrastructure: An Analysis for 2030*. Bonn: UNFCCC.
- Nicholls, R. J., and A. Cazenave. 2010. Sea-Level Rise and Its Impact on Coastal Zones. *Science*. 328(5985). pp. 1517–1520.

- Norwegian Refugee Council. 2015. *Community Resilience and Disaster-Related Displacement in South Asia*. Oslo: Norwegian Refugee Council.
- Obeyskera, J., and J. Park. 2013. Scenario-Based Projection of Extreme Sea Levels. *Journal of Coastal Research*. 286. pp. 1–7.
- Obokata, R., L. Veronis, and R. McLeman. 2014. Empirical Research on International Environmental Migration: A Systematic Review. *Population and Environment*. 36(1). pp. 111–135.
- Orlić, M., and Z. Pasarić. 2013. Semi-empirical versus Process-Based Sea-Level Projections for the Twenty-First Century. *Nature Climate Change*. pp. 1–4.
- Otto, C., et al. 2016. *Acclimate – A Dynamic Model for Economic Loss-Propagation*. Potsdam, Germany: Potsdam Institute for Climate Impact Research.
- Pacific Small Island Developing States. 2009. *Views on the Possible Security Implications of Climate Change to be included in the report of the Secretary-General to the 64th Session of the United Nations General Assembly*. New York: United Nations.
- Park, G. A., et al. 2009. Future Potential Impacts of Climate Change on Agricultural Watershed Hydrology and the Adaptation Strategy of Paddy Rice Irrigation Reservoir by Release Control. *Paddy and Water Environment*. 7(4). pp. 271–282.
- Pender, J. 2007. Community-Led Adaptation in Bangladesh. *Forced Migration Review*. 31. pp. 54–55.
- Perelet, R. 2007. *Central Asia: Background Paper on Climate Change*. Human Development Report Office. New York: United Nations Development Programme.
- Peyrouse, S. 2013. *Food Security in Central Asia: A Public Policy Challenge*. Washington, DC: Elliott School of International Affairs, George Washington University.
- Portmann, F. T., et al. 2013. Impact of Climate Change on Renewable Groundwater Resources: Assessing the Benefits of Avoided Greenhouse Gas Emissions Using Selected CMIP5 Climate Projections. *Environmental Research Letters*. 8(2). 24023.
- Presutti, W. D. J. 1992. The Single Source Issue: US and Japanese Sourcing Strategies. *International Journal of Purchasing and Materials Management*. 228(1). pp. 2–9.
- Primavera, J. H., R. N. Rollon, and M. S. Samson. 2011. The Pressing Challenges of Mangrove Rehabilitation: Pond Reversion and Coastal Protection. *Treatise on Estuarine and Coastal Science – Volume 10: Ecohydrology and Restoration*.
- Prudhomme, C., et al. 2013. Hydrological Droughts in the 21st Century, Hotspots and Uncertainties from a Global Multimodel Ensemble Experiment. *Proceedings of the National Academy of Sciences*. 111. pp. 3262–3267.
- Quinn, J. B., and F. G. Hilmer. 1994. Strategic Outsourcing. *Sloan Management Review*. 35(4). pp. 43–55.
- Rahman, S., and M. A. Rahman. 2015. Climate Extremes and Challenges to Infrastructure Development in Coastal Cities in Bangladesh. *Weather Climate Extremes*. 7. pp. 96–108.
- Raleigh, C., and H. Urdal. 2007. Climate Change, Environmental Degradation and Armed Conflict. *Political Geography*. 26(6). pp. 674–694.
- Rasul, G., et al. 2012. Vulnerability of the Indus Delta to Climate Change in Pakistan. *Pakistan Journal of Meteorology*. 8(16). pp. 89–107.
- Reid, H. 2015. Ecosystem- and Community-Based Adaptation: Learning from Community-Based Natural Resource Management. *Climate and Development*. 8. pp. 4–9.
- Ren, G. Y., et al. 2007. Implications of Temporal Change in Urban Heat Island Intensity Observed at Beijing and Wuhan Stations. *Geophysical Research Letters*. 34(5). pp. 1–5.
- Reuveny, R. 2007. Climate Change-Induced Migration and Violent Conflict. *Political Geography*. 26(6). pp. 656–673.
- Reyer, C.P.O. et al. 2015. Climate Change Impacts in Central Asia and Their Implications for Development. *Regional Environmental Change*. 1–12.
- Roaf, S., D. Crichton, and F. Nicol. 2005. *Adapting Buildings and Cities for Climate Change*. Burlington: Elsevier.
- Rogers, S., and T. Xue. 2015. Resettlement and Climate Change Vulnerability: Evidence from Rural China. *Global Environmental Change*. 35. pp. 62–69.
- Rosenzweig, C., et al. 2013. Assessing Agricultural Risks of Climate Change in the 21st Century in a Global Gridded Crop Model Intercomparison. *Proceedings of the National Academy of Sciences*. 111. pp. 3268–3273.
- Sabban, R. 2002. *United Arab Emirates: Migrant Women in the United Arab Emirates: The Case of Female Domestic Workers*. Geneva: International Labor Office.
- Saha, S. 2012. Security Implications of Climate Refugees in Urban Slums: A Case Study from Dhaka, Bangladesh. In J. Scheffran et al., eds. *Climate Change, Human Security and Violent Conflict: Challenges for Societal Stability*. Heidelberg and Berlin: Springer. pp. 595–611.

- Sano, M., et al. 2015. Coastal Vulnerability and Progress in Climate Change Adaptation: An Australian Case Study. *Regional Studies in Marine Science*. 2. pp. 113–123.
- Santamouris, M. 2015. Analyzing the Heat Island Magnitude and Characteristics in One Hundred Asian and Australian Cities and Regions. *Science of the Total Environment*. 512–513. pp. 582–598.
- Sarrat, C., et al. 2006. Impact of Urban Heat Island on Regional Atmospheric Pollution. *Atmospheric Environment*. 40(10). pp. 1743–1758.
- Satterthwaite, D., et al. 2007. *Adapting to Climate Change in Urban Areas: The Possibilities and Constraints in Low and Middle Income Nations*. London: International Institute for Environment and Development.
- Sayama, T., et al. 2012. Rainfall–Runoff–Inundation Analysis of the 2010 Pakistan Flood in the Kabul River Basin. *Hydrological Sciences Journal*. 57(2). pp. 298–312.
- Scheffran, J. 2014. Climate Change and Security in South Asia and the Himalaya Region: Challenges of Conflict and Cooperation. In S. Aneel, U. T. Haroon, and I. Niazi, eds. *Sustainable Development in South Asia: Shaping the Future*. Islamabad: Sustainable Development Policy Institute and Sang-e-Meel Publishers. pp. 439–458.
- Scheffran, J. 2015. *Climate Change as a Risk Multiplier in a World of Complex Crises*. Working paper prepared for the Conference Planetary Security, The Hague, Nov. 2–3, 2015 The Hague.
- Scheffran, J., E. Marmer, and P. Sow. 2012. Migration as a Contribution to Resilience and Innovation in Climate Adaptation: Social Networks and Co-development in Northwest Africa. *Applied Geography*. 33. pp. 119–127.
- Schewe, J., et al. 2014. Multimodel Assessment of Water Scarcity under Climate Change. *Proceedings of the National Academy of Sciences*. 111(9). pp. 3245–3250.
- Schleussner, C.-F., et al. 2016. Armed-Conflict Risks Enhanced by Climate-Related Disasters in Ethnically Fractionalized Countries. *Proceedings of the National Academy of Sciences*. 113(33). pp. 9216–9221.
- Schellnhuber, H. J., et al. 2014. *Turn Down the Heat: Confronting the New Climate Normal*. Washington, DC: World Bank.
- Schlüter, M., D. Hirsch, and C. Pahl-Wostl. 2010. Coping with Change: Responses of the Uzbek Water Management Regime to Socio-Economic Transition and Global Change. *Environmental Science & Policy*. 13(7). pp. 620–636.
- Schmidhuber, J., and F. N. Tubiello. 2007. Global Food Security under Climate Change. *Proceedings of the National Academy of Sciences*. 104(50). pp. 19703–19708.
- Schnell, M. K., and D.E. Weinstein. 2012. *Evaluating the Economic Response to Japan's Earthquake*. Tokyo. The Research Institute of Economy, Trade, and Industry.
- Seto, K. C. 2011. Exploring the Dynamics of Migration to Mega-Delta Cities in Asia and Africa: Contemporary Drivers and Future Scenarios. *Global Environmental Change*. 21. pp. S94–S107.
- Shah, J. 2013a. *Tajikistan: Overview of Climate Change Activities*. Washington, DC: World Bank.
- . 2013b. *Turkmenistan: Overview of Climate Change Activities*. Washington, DC: World Bank.
- Shah, J., et al. 2013a. *Kazakhstan: Overview of Climate Change Activities*. Washington, DC: World Bank.
- Shah, J., et al. 2013b. *Kyrgyz Republic: Overview of Climate Change Activities*. Washington, DC: World Bank.
- Shah, T. 2009. Climate Change and Groundwater: India's Opportunities for Mitigation and Adaptation. *Environmental Research Letters*. 4(3).
- Shaw, R., et al. 2016. *Urban Disasters and Resilience in Asia*. Oxford: Elsevier.
- Sheffi, Y., and J. B. Rice. 2005. A Supply Chain View of the Resilient Enterprise. *Sloan Management Review*. 47(1). pp. 41–48.
- Shen, S., and T. Binns. 2012. Pathways, Motivations and Challenges: Contemporary Tuvaluan Migration to New Zealand. *GeoJournal*. 77(1). pp.63–82.
- de Sherbinin, A., et al. 2012. Migration and Risk: Net Migration in Marginal Ecosystems and Hazardous Areas. *Environmental Research Letters*. 7.
- Siegfried, T., et al. 2012. Will Climate Change Exacerbate Water Stress in Central Asia? *Climatic Change*. 112(3–4). pp. 881–899.
- Silverman, J., et al. 2009. Coral Reefs May Start Dissolving When Atmospheric CO₂ Doubles. *Geophysical Research Letters*. 36(5). p. L05606.
- Smajgl, A., et al. 2015. Responding to Rising Sea Levels in the Mekong Delta. *Nature Climate Change*. 5(2). pp. 167–174.
- Sommer, R., et al. 2013. Impact of Climate Change on Wheat Productivity in Central Asia. *Agriculture, Ecosystems & Environment*. 178. pp. 78–99.
- Sovacool, B. K. 2014. *Environmental Issues, Climate Changes, and Energy Security in Developing Asia*. Manila: Asian Development Bank.
- Strassburg, M. W., et al. 2015. Sea Level Trends in Southeast Asian Seas. *Climate of the Past*. 11(5). pp. 743–750.

- Susskind, L. 2010. Policy and Practice: Responding to the Risks Posed by Climate Change: Cities Have No Choice but to Adapt. *Town Planning Review*. 81. pp. 217–235.
- Sutton, W., J. Srivastava, and J. Neumann. 2013. *Looking Beyond the Horizon. How Climate Change Impacts and Adaptation Responses Will Reshape Agriculture in Eastern Europe and Central Asia*. Washington, DC: World Bank.
- Sutton, W., et al. 2013. *Reducing the Vulnerability of Uzbekistan's Agricultural Systems to Climate Change. Impact Assessment and Adaptation Options*. Washington, DC: World Bank.
- Swift, C. O. 1995. Preferences for Single Sourcing and Supplier Selection Criteria. *Journal of Business Research*. 32(2). pp. 105–111.
- Tacoli, C. 2009. Crisis or Adaptation? Migration and Climate Change in a Context of High Mobility. *Environment and Urbanization*. 21(2). pp. 513–525.
- Tang, C., and B. Tomlin. 2008. The Power of Flexibility for Mitigating Supply Chain Risks. *International Journal of Production Economics*. 116(1). pp. 12–17.
- Tanner, T., et al. 2009. *Urban Governance for Adaptation: Assessing Climate Change Resilience in Ten Asian Cities*. Brighton: Institute of Development Studies.
- Teixeira, E. I., et al. 2013. Global Hot-Spots of Heat Stress on Agricultural Crops due to Climate Change. *Agricultural and Forest Meteorology*. 170. pp. 206–215.
- Timmerman, J. G., et al. 2011. Adaptation to Climate Change: Challenges for Transboundary Water Management. In J. G. Timmerman, ed. *Adaptation to Climate Change: Challenges for Transboundary Water Management*. Springer Link. pp. 523–541.
- Tol, R. S. J. 2002. Estimates of the Damage Costs of Climate Change: Part 1: Benchmark Estimates. *Environmental and Resource Economics*. 21(1). pp. 47–73.
- Tomlin, B. 2006. On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks. *Management Science*. 52. pp. 639–657.
- Tompkins, E. L., and W. N. Adger. 2004. Does Adaptive Management of Natural Resources Enhance Resilience to Climate Change? *Ecology and Society*. 9.
- Tran, H., et al. 2006. Assessment with Satellite Data of the Urban Heat Island Effects in Asian Mega Cities. *International Journal of Applied Earth Observation and Geoinformation*. 8(1). pp. 34–48.
- Treleven, M. 1987. Single Sourcing: A Management Tool for the Quality Supplier. *International Journal of Purchasing and Materials Management*. 23(1). pp. 19–24.
- Trilateral Working Group on Coastal Protection and Sea Level Rise (CPSL). 2010. *CPSL Third Report. The Role of Spatial Planning and Sediment in Coastal Risk Management*. Wadden Sea Ecosystem No. 28. Wilhelmshaven, Germany: Common Wadden Sea Secretariat, CPSL.
- Turrall, H., J. Burke, and J. M. Faurès. 2011. *Climate Change, Water and Food Security*. Rome: Food and Agriculture Organization of the United Nations.
- von Uexkull, N., et al. 2016. Civil Conflict Sensitivity to Growing-Season Drought. *Proceedings of the National Academy of Sciences*. 113 (44). pp. 12391–12396.
- United Nations. 2015. *The Millennium Development Goals Report 2015*. New York.
- United Nations Department of Economic and Social Affairs Population Division (UN DESA). 2014. *World Urbanization Prospects*. New York: United Nations.
- . 2015. *World Population Prospect: The 2015 Revision*. World Population 2015 Wallchart.
- United Nations Development Programme (UNDP), Bureau for Crisis Prevention and Recovery. 2011. *Disaster-Conflict Interface: Comparative Experiences*. New York, NY.
- UNESCO International Hydrological Programme. 2015. *Groundwater and Climate Change - Small Island Developing States (SIDS)*. Geneva: UNESCO.
- United Nations General Assembly. 2009. *Climate Change and its Possible Security Implications*. New York: United Nations.
- United States Agency for International Development (USAID). 2013. *Mekong Adaptation and Resilience to Climate Change Synthesis Report*. Washington, DC.
- United States Department of Defense. 2015. *National Security Implications of Climate-Related Risks and a Changing Climate*. Washington, DC.
- United States Global Change Research Program (USGCRP). 2016. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Washington, DC: USGCRP.
- Uprety, K., and S. M. A. Salman. 2011. Legal Aspects of Sharing and Management of Transboundary Waters in South Asia: Preventing Conflicts and Promoting Cooperation. *Hydrological Sciences Journal*. 56(4). pp. 641–661.
- van Panhuis, W. G., et al. 2015. Region-wide Synchrony and Traveling Waves of Dengue across Eight Countries in Southeast Asia. *Proceedings of the National Academy of Sciences*. 112(42). pp. 13069–13074.

- Vardoulakis, S., et al. 2014. Comparative Assessment of the Effects of Climate Change on Heat- and Cold-Related Mortality in the United Kingdom and Australia. *Environmental Health Perspectives*. 122(12). pp. 1285–1292.
- Victora, C. G., et al. 2008. Maternal and Child Undernutrition: Consequences for Adult Health and Human Capital. *Lancet*. 371(9609). pp. 340–357.
- Vinke, K., et al. 2016. Climatic Risks and Impacts in South Asia: Extremes of Water Scarcity and Excess. *Regional Environmental Change*. pp. 1–15.
- Vivekananda, J. 2011. *Practice Note: Conflict-sensitive Responses to Climate Change in South Asia*. London: Initiative for Peacebuilding.
- Vivekananda, J., et al. 2014. On shrimp, Salt and Security: Livelihood Risks and Responses in South Bangladesh and East India. *Environment, Development and Sustainability*. 16(6). pp. 1141–1161.
- Wakolbinger, T., and J. M. Cruz. 2011. Supply Chain Disruption Risk Management through Strategic Information Acquisition and Sharing and Risk-Sharing Contracts. *International Journal of Production Research*. 49(13). pp. 4063–4084.
- Waldinger, M., and S. Fankhauser. 2015. *Climate Change and Migration in Developing Countries: Evidence and Implications for PRISE Countries*. Leeds: The Centre for Climate Change Economics and Policy.
- Walsham, M. 2010. *Assessing the Evidence: Environment, Climate Change and Migration in Bangladesh*. Dhaka: International Organization for Migration.
- Ward, R., and N. Ranger. 2010. *Trends in Economic and Insured Losses from Weather-Related Events*. Insurance Industry Brief. November. The Munich Re Programme of the Centre for Climate Change Economics and Policy.
- Warnecke, A., D. Tänzler, and R. Vollmer. 2010. Climate Change, Migration and Conflict: Receiving Communities under Pressure. *Climate Change and Migration*. June. Washington, DC: The German Marshall Fund of the United States.
- Warner, K. 2010. Global Environmental Change and Migration: Governance Challenges. *Global Environmental Change*. 20(3). pp. 402–413.
- . 2011. Environmental Change and Migration: Methodological Considerations from Ground-Breaking Global Survey. *Population and Environment*. 33(1). pp. 3–27.
- Warszawski, L., et al. 2013. A Multi-Model Analysis of Risk of Ecosystem Shifts under Climate Change. *Environmental Research Letters*. 8(4). p. 44018.
- Wassmann, R., et al. 2009a. Climate Change Affecting Rice Production: The Physiological and Agronomic Basis for Possible Adaptation Strategies. *Advances in Agronomy*. 101. pp. 59–122.
- Wassmann, R., et al. 2009b. Regional Vulnerability of Climate Change Impacts on Asian Rice Production and Scope for Adaptation. *Advances in Agronomy*. 102. pp. 91–133.
- Watts, N., et al. 2015. Health and Climate Change: Policy Responses to Protect Public Health. *Lancet*. 386(10006). pp. 1861–1914.
- WBGU. 2007. *Climate Change as a Security Risk*. Berlin, Heidelberg, New York: German Advisory Council on Global Change. Springer Verlag.
- Wee, H. M., and S. Wu. 2009. Lean Supply Chain and Its Effect on Product Cost and Quality: A Case Study on Ford Motor Company. *Supply Chain Management*. 14(5). pp. 335–341.
- Wenz, L., and A. Levermann. 2016. Enhanced Economic Connectivity to Amplify Heat-Stress-Related Losses. *Science Advances*. 2(6).
- Wenz, L., et al. 2014. Acclimate – A Model of Economic Damage Propagation. Part II: A Dynamic Formulation of the Backward Effects of Disaster Induced Production Failures in the Global Supply Network. *Environment Systems and Decisions*. 34(1). pp. 525–539.
- Wilby, R. L. 2007. A Review of Climate Change Impacts on the Built Environment. *Built Environment*. 33. pp. 31–45.
- Williams, A. 2008. Turning the Tide: Recognizing Climate Change Refugees in International Law. *Law Policy*. 30(4). pp. 502–529.
- Wischnath, G., and H. Buhaug. 2014. On Climate Variability and Civil War in Asia. *Climatic Change*. 122(4). pp. 709–721.
- Wong, P. P., et al. 2013. Coastal Systems and Low-Lying Areas. In: *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. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 361–409.
- World Bank. 2010a. *Economics of Adaptation to Climate Change: Country Study Bangladesh*. Washington, DC.

- . 2010b. *Economics of Adaptation to Climate Change: Country Study Vietnam*. Washington, DC.
- . 2013a. *Annual Freshwater Withdrawals, Agriculture*. Washington, DC.
- . 2013b. *Turn Down the Heat: Climate Extremes, Regional Impacts and the Case for Resilience*. Washington, DC.
- . 2014. *Urban Development*. Washington, DC.
- . 2016. *World Development Indicators*. Washington, DC.
- World Health Organization (WHO). 2014. *Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s*. Geneva.
- . 2016. *Dengue and Severe Dengue*. Geneva.
- Wu, G., et al. 2012. Climate Protection and China's Energy Security: Win-Win or Tradeoff. *Applied Energy*. 97. pp. 157–163.
- Yang, L., et al. 2014. Climate-Related Flood Risks and Urban Responses in the Pearl River Delta, China. *Regional Environmental Change*. 15(2). pp. 379–391.
- Yang, L., et al. 2016. Contrasting Impacts of Urban Forms on the Future Thermal Environment: Example of Beijing Metropolitan Area. *Environmental Research Letters*. 11(3). pp. 34018.
- Yonetani, M. 2014. *Global Estimates 2014: People Displaced by Disasters*. Geneva: IDMC.
- Yonetani, M., and L. Yuen. 2014. *The Evolving Picture of Displacement in the Wake of Typhoon Haiyan*. Department of Social Welfare and Development, Government of the Philippines. Manila.
- Yu, W. H., et al. 2010. *Climate Change Risks and Food Security in Bangladesh*. Washington, DC: World Bank.
- Zarfl, C., et al. 2015. A Global Boom in Hydropower Dam Construction. *Aquatic Sciences*. 77(1). pp. 161–170.
- Zhang, D. D., et al. 2007. Global Climate Change, War, and Population Decline in Recent Human History. *Proceedings of the National Academy of Sciences*. 104(49). pp. 19214–19219.
- Zhao, L., R. Ding, and J. C. Moore. 2014. Glacier Volume and Area Change by 2050 in High Mountain Asia. *Global Planetary Change*. 122. pp. 197–207.



CONCLUSION



The severity of climate change impacts on human systems becomes particularly evident in the analysis of observed and future changes in the Asia and Pacific region. The deterioration of the Asian “water towers,” prolonged heat waves, coastal sea-level rise, and changes in rainfall patterns could disrupt ecosystem services and lead to severe effects on livelihoods, which in turn would affect human health, migration patterns, and the potential for conflicts. Some areas, particularly in Southeast Asia, could enter into new climate regimes due to the frequent occurrence of unprecedented heat extremes. Already, small island developing countries in the Pacific as well as Asia’s coastlines have experienced an increase in the occurrence and magnitude of storms and storm surges, coastal flooding, and saltwater intrusion. Simultaneously, other parts of the region are highly exposed and vulnerable to the observed intensification of heat waves and droughts. The poor, women, children, and the elderly are disproportionately affected by these changes. Unabated climate change threatens to undo many of the development advancements of the last decades, not least by incurring high economic losses.

Numerous countries of the region regularly experience annual losses associated with extreme weather events equivalent to over 1% of GDP. Unless urgent action is taken to strengthen resilience and to avoid global warming beyond 2°C, climate change will multiply such losses.

Further research is needed to identify the nature and extent of both the impacts of climate change as well as the interventions necessary to improve resilience to these impacts. However, there is no uncertainty over the adverse effects of observed changes on development in Asia and the Pacific, and over the threat of unrestrained climate change undermining the socioeconomic progress of the region. The findings presented in this report highlight the severity of the projected consequences of climate change in Asia and the Pacific. Even under a Paris consensus scenario, large investments in adaptation will be necessary. The magnitude of the challenge for the people of the region is immense, with the livelihoods and welfare of hundreds of millions of people at stake.

ADB and its developing member countries have long recognized that the region must proactively achieve climate resilience in line with the Sustainable Development Goals, the Paris Agreement on climate change, and the Sendai Framework for Disaster Risk Reduction to avoid the worst impacts of climate change.

In September 2015, ADB committed to double its climate finance from its own resources to \$6 billion by 2020, including \$2 billion for adaptation. Asia’s share of global emissions is increasing. Without rapid and full decarbonization of the global economy, the targets set in the Paris Agreement will not be met. As this report shows, a business-as-usual scenario will lead to disastrous climate impacts for the people of Asia and the Pacific, especially for poor and vulnerable populations. ADB will therefore invest \$4 billion by 2020 in climate mitigation, fostering renewable energy supply and green growth across the region. With the adoption of its Climate Change Operational Framework 2030, ADB aims to scale up support to its member countries and ensure that climate change considerations are fully mainstreamed, not only in corporate strategies and policies, sector and thematic operational plans, and country programming, but also in project design, implementation, monitoring, and evaluation. ADB will also ensure that roles and responsibilities across the institution are clearly defined to ensure the effective implementation of ADB’s climate change agenda.

Building further on results, lessons, and successes achieved thus far, the above commitments will enable ADB to continue working effectively with its DMCs and other partners to establish systematic approaches to climate risk management. This will mean exploring opportunities to strengthen climate change adaptation measures in planning and investments across sectors and themes, including agriculture, food security and rural development, water resources, and social and urban development. ADB will also continue to work with its DMCs to embed measures to address extreme weather events in the design and implementation of its investment projects, programs, capacity building-related assistance, and knowledge products, helping counteract the added risks arising from climate change.

A Region at Risk

The Human Dimensions of Climate Change in Asia and the Pacific

Asia and the Pacific continues to be exposed to climate change impacts. Home to the majority of the world's poor, the population of the region is particularly vulnerable to those impacts. Unabated warming could largely diminish previous achievements of economic development and improvements, putting the future of the region at risk. Read the most recent projections pertaining to climate change and climate change impacts in Asia and the Pacific, and the consequences of these changes to human systems, particularly for developing countries. This report also highlights gaps in the existing knowledge and identifies avenues for continued research.

About the Asian Development Bank

ADB's vision is an Asia and Pacific region free of poverty. Its mission is to help its developing member countries reduce poverty and improve the quality of life of their people. Despite the region's many successes, it remains home to a large share of the world's poor. ADB is committed to reducing poverty through inclusive economic growth, environmentally sustainable growth, and regional integration.

Based in Manila, ADB is owned by 67 members, including 48 from the region. Its main instruments for helping its developing member countries are policy dialogue, loans, equity investments, guarantees, grants, and technical assistance.

About the Potsdam Institute for Climate Impact Research

The Potsdam Institute for Climate Impact Research (PIK), founded in 1992, is a non-profit research institute addressing crucial scientific questions in the fields of global change, climate impacts and sustainable development. The institute is a member of the Leibniz Association and conducts interdisciplinary research, generating sound information for decision-making.



ASIAN DEVELOPMENT BANK

6 ADB Avenue, Mandaluyong City
1550 Metro Manila, Philippines
www.adb.org