Economic development and declining vulnerability to climate-related disasters in China

Environmental Research Letters

LETTER

Economic development and declining vulnerability to climate-related disasters in China

CrossMark

OPEN ACCESS

RECEIVED
10 June 2017

REVISED
21 January 2018

ACCEPTED FOR PUBLICATION
31 January 2018

PUBLISHED
22 February 2018

Jidong Wu[1,2,5], **Guoyi Han**[3], **Hongjian Zhou**[4] **and Ning Li**[1,2]

[1] Key Laboratory of Environmental Change and Natural Disaster, MOE & MCA, Beijing Normal University, Beijing 100875, People's Republic of China
[2] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, People's Republic of China
[3] Stockholm Environment Institute, Linnégatan 87D, 115 23 Stockholm, Sweden
[4] National Disaster Reduction Center of China, MCA, Beijing, 100124, People's Republic of China
[5] Author to whom any correspondence should be addressed.

E-mail: wujidong@bnu.edu.cn

Keywords: climate change, natural disasters, vulnerability, direct economic losses (DELs), economic development

Abstract

Exposure and vulnerability are the main contributing factors of growing impact from climate-related disasters globally. Understanding the spatiotemporal dynamic patterns of vulnerability is important for designing effective disaster risk mitigation and adaptation measures. At national scale, most cross-country studies have suggested that economic vulnerability to disasters decreases as income increases, especially for developing countries. Research covering sub-national climate-related natural disasters is indispensable to obtaining a comprehensive understanding of the effect of regional economic growth on vulnerability reduction. Taking China as a case, this subnational scale study shows that economic development is correlated with the significant reduction in human fatalities but increase in direct economic losses (DELs) from climate-related disasters since 1949. The long-term trend in climate-related disaster vulnerability, reflected by mortality (1978–2015) and DELs (1990–2015) as a share of the total population and Gross Domestic Product, has seen significant decline among all economic regions in China. While notable differences remain among its West, Central and East economic regions, the temporal vulnerability change has been converging. The study further demonstrated that economic development level is correlated with human and economic vulnerability to climate-related disasters, and this vulnerability decreased with the increase of per-capita income. This study suggested that economic development can have nuanced effects on overall human and economic vulnerability to climate-related disasters. We argue that climate change science needs to acknowledge and examine the different pathways of vulnerability effects related to economic development.

1. Introduction

Between 1970 and 2012, the global direct economic losses (DELs) caused by climate-related disasters reached US$ 2.4 trillion (in 2012 prices), and deaths exceeded 1.94 million (WMO 2014). Global climate-related disaster losses have seen increasing trend over the past decades, largely due to increased exposure of people and assets driven by economic development and population growth (Mills 2005, IPCC 2012). Furthermore, the vulnerability to disasters also varies notably along the development spectrum (Anbarci *et al* 2005, Kellenberg and Mobarak 2008, Hsiang and Narita 2012, Anttila-Hughes and Hsiang 2013, Hsiang and Jina 2013, Ferreira *et al* 2013, Jongman *et al* 2015, Tanoue *et al* 2016, Geiger *et al* 2016). While the least developed and low-income countries take up 65% of worldwide natural disaster deaths from 1985–1999 (IPCC 2001), the adverse economic growth impact of climatic disasters is more obvious in developing countries than developed countries (Klompa and Valckx 2014). While evidently related, how economic development contributed to reduce the vulnerability of natural disasters remains elusive.

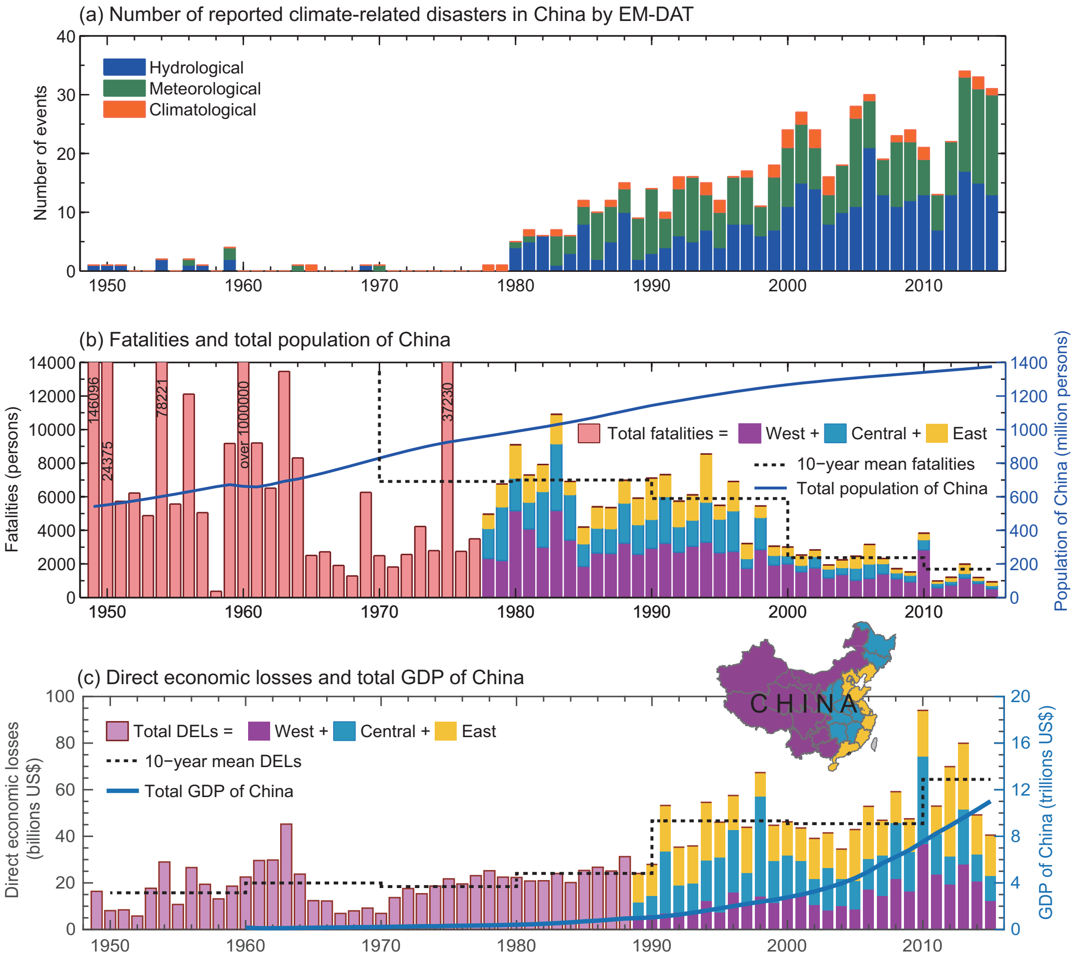

Figure 1. Climate-related natural disaster impacts in mainland China. (*a*) Number of climate-related disasters for each subgroup (bar) reported in the Emergency Events Database (EM-DAT) from 1949–2015. (*b*) Temporal change in fatalities for the West, Central and East regions from 1978–2015 and for China as a whole from 1949–1977 (bar), and fatalities in ten-year average (dash line), and total population growth of China (solid line). See section 2 for a detailed interpretation of the construction of the climate-related disaster impact series for (*b*) and (*c*), which are mainly based on reported natural disaster impacts from various Chinese government agencies. (*c*) Same as (*b*) but for reported DELs, total GDP of China data are from the China Statistical Yearbook (adjusted to 2015 price level). East, Central and West economic zone divisions are adopted following the definition of the Chinese Ministry of Housing and Urban–Rural Development (MHURD 2015) as shown in the upper right corner of (*c*).

Mindful of the complexity of vulnerability to disaster risks, for the discussion and analysis in this study, we define vulnerability to natural disaster simply by fatalities and DELs, measured by its share of the exposed population and asset value, respectively (Jongman *et al* 2015, Tanoue *et al* 2016). Defined as such, past empirical studies at national scale broadly agree the importance of economic development in reducing vulnerability to natural disasters (Kahn 2005, Padli *et al* 2010, Toya and Skidmore 2007, Rashky 2008, Schumacher and Strobl 2011, Cavallo *et al* 2013, Fankhauser and McDermott 2014, Zhou *et al* 2014, Huang 2014, Park *et al* 2015, Garschagen and Romero-Lankao 2015), including the key findings of two more recent studies that analyzed the spatiotemporal patterns of flood vulnerability around the world with combined innovative dynamic flood hazard and exposure modeling techniques (Jongman *et al* 2015, Tanoue *et al* 2016). These works however did not provide the causal links between economic growth and natural disaster impacts.

Aiming to contribute on whether there is a clearly detectable pattern of co-relationship between the level of economic development and the human vulnerability to climate-related disasters, this study examines the sub-national regional data from China, one of the transition countries, over the past decades. Based on the substantial differences in economic development, we grouped 31 mainland provinces into three major economic regions—West (11 provinces), Central (nine provinces) and East (11 provinces) (figure 1). The main purpose of the study is to map how vulnerability trend has changed in space and time, and to explore how the changes of the vulnerability relate to income. To do so, we first mapped historical trends of absolute fatality and DELs against population growth and economic growth for the three economic regions and China as a whole. Second, we calculated mortality rate (fatalities as a share of total population) and direct economic loss rate (DELs as percent of total GDP) as vulnerability indicators, in turn, mapped the historical change of vulnerability for the three economic zones and China as a whole. Lastly, we illustrate the statistical relation between per capita GDP and vulnerability to climate-related disasters in China.

2. Methods

2.1. Data sources

This study used two types of data. First, natural disaster impacts records during 1949–2015 were retrieved from published statistical yearbooks and relevant references, which reported the direct impacts of natural disasters that measured by deaths and DELs, DELs are measured by the repair and replacement costs required to restore the affected properties (e.g. houses, roads, equipment), which does not include other indirect time-element economic losses (e.g. output losses due to business interruption) and environmental impacts (e.g. natural resource damage). The main natural disaster types in China include drought, earthquake, heavy snow, flood, mass movement wet (including rock fall, avalanche, landslide and mudslide) and storm (including typhoon, wind and hail). In this paper, we treat all these, except earthquake, as climate-related natural disasters. These disaster impacts data were from three sources:

i. The recorded annual provincial (31 provinces in the mainland China) total deaths (1978–2015) and total DELs (1989–2015) caused by natural disasters in China were obtained from China's Civil Affairs Statistical Yearbook (Ministry of Civil Affairs, various years, via data.cnki.net) published by Chinese Statistics Press.

ii. Earthquake disaster event impact records (1978–2015) from China Earthquake Yearbook (China Earthquake Administration, various years), which is published by Chinese Seismological Press, and these records include information on the deaths and DELs by counties.

iii. National total deaths (1949–1977) and DELs (1949–1988) data for climate-related natural disaster were complemented by statistical information from the State Scientific and Technological Commission of Major Natural Disasters (SSTCND 1994, Wu *et al* 2014), which systematically summarized the natural disaster impacts by main natural disaster types from 1949–1990 for China as a whole.

Second, economic and social development data of China that including: (i) historical provincial GDP and population data were collected from the China Statistical Yearbook of National Bureau of Statistics of China (www.stats.gov.cn), (ii) the consumer price index (CPI) and the GDP deflator of China provided by the World Development Indicators from the World Bank (http://data.worldbank.org/data-catalog/world-development-indicators). For the sake of spatiotemporal comparisons, original reported nominal DELs (in China Yuan) were deflated to the 2015 year price level according to the CPI. GDP is also deflated to the 2015 year price level by the GDP deflator.

2.2. Extraction of climate-related disaster impact data

The annual natural disaster impact (deaths and DELs) records by disaster types and by province are only available since 2007, thus, we resort to generate the climate-related natural disaster impact data series ($\mathrm{Loss}_{\mathrm{climate}}$, i.e. deaths or DELs) based on disaster impact records from all natural disasters as a whole ($\mathrm{Loss}_{\mathrm{disasters}}$) and earthquakes alone ($\mathrm{Loss}_{\mathrm{earthquake}}$) as described above, respectively (Wu *et al* 2014),

$$\mathrm{Loss}_{\mathrm{climate}} = \mathrm{Loss}_{\mathrm{disasters}} - \mathrm{Loss}_{\mathrm{earthquake}}. \quad (1)$$

Finally, deaths (1978–2015) and DELs (1990–2015) data for climate-related disasters by year/province can be constructed and then aggregated to the West, Central and East regions.

2.3. Vulnerability calculation

Due to different conceptual frameworks and disciplinary views, definitions to vulnerability also differ (Adger 2006, Cutter and Finch 2008, Simelton *et al* 2009, IPCC 2012, Fraser *et al* 2013, Koks *et al* 2015, UNISDR 2017). In this paper, vulnerability means '*the degree of loss to each element should a hazard of a given severity occur.*' (Coburn *et al* 1994) that is dynamic and varying across temporal and spatial scales and arising from various physical, social, economic, and environmental factors (IPCC 2012). Vulnerability can be computed as a percentage of losses as compared with total exposure (Peduzzi *et al* 2012, Hallegatte *et al* 2013, Jongman *et al* 2015). As such, climate-related disaster vulnerability is defined according to the mortality rate (the ratio of the reported fatalities to the exposed population) and direct economic loss rate (the percentage of the reported DELs to the exposed GDP),

$$\mathrm{Vulnerability} = \frac{\mathrm{Loss}_{\mathrm{climate}}\,(\text{deaths or DELs})}{\mathrm{E}_{\mathrm{exposed}}\,(\text{population or GDP})}, \quad (2)$$

where $\mathrm{E}_{\mathrm{exposed}}$ is the situation of people, infrastructure, housing and other tangible human assets located in (a particular) hazard-prone areas (UNISDR 2017). Population and GDP are used as exposure indicators in this paper. Measuring exposure is not easy (e.g. Wu *et al* 2017), for floods as an example, exposed population or GDP can be modelled using maximum inundation map combined with population or GDP maps (Jongman *et al* 2015). While for a group of climate-related disasters as in this study, this exposure estimation is extremely a difficult task due to large amount of hazard data needed. As such, we supposed that for each province it was hit by one or more climate-related disaster sub-types in each year, total population or GDP was defined as an exposure measurement indicator for the vulnerability calculation (equation 2), which will induce exposure measurement bias, and affect the vulnerability value, this uncertainty will be discussed in section 4.

This study performs a sub-national (i.e. West, Central and East) analysis of the relationship between economic development and climate-related disasters. Regional exposure is the accumulated value of GDP or population in the provinces that belong to the region. China is generally divided into East, Central and West regions according to the economic development levels and geographical locations of each province, and the East region is generally accepted as the most developed area, with the Central and West regions representing underdeveloped and less-developed regions, respectively.

Finally, these values were converted to US dollars (US\$) using the exchange rates between China Yuan and US\$ in 2015 (i.e. 1 US\$ = 6.2284 China Yuan). For each year of analysis, provincial disaster impact and exposure data were summed on a region level. For each region (West, Central or East), the mortality and direct economic loss rates (vulnerability) can be calculated as the ratio of reported fatalities and DELs for the exposed population and GDP. The Mann–Kendall trend test is used in this study as the significance test for the disaster impact trend.

3. Results

3.1. Climate-related disaster impact and exposure in China

The number of climate-related disaster events in China, as reported in the Emergency Events Database (EM-DAT), has increased notably since the 1980s (figure 1(*a*)). Here we group the subcategories of hydrological (like floods and landslides), meteorological (like tropical cyclone) and climatological disasters together as the climate-related disasters. However, the fatalities and DELs reported before 1980 (figures 1(*b*) and (*c*)) are not consistent with the number of reported disaster events (figure 1(*a*)) because fewer disaster events were recorded before 1980 owing to limited data accessibility and information gathering, thus, many events were not recorded in the EM-DAT, which partially explains the seemingly drastic increase in reported disaster events since 1980.

For annual total number of reported fatalities, there is a clear declining trend ($p < 0.001$, Mann–Kendall test) since the founding of the People's Republic of China of 1949–2015. The decrease surpassed 5.8% per year during 1978–2015 and 4.4% per year since 1990 as indicated by the bar in figure 1(*b*), which means that the death toll number reduced by 224 per year since 1978. Ten-year mean fatality statistics show that the average annual total fatalities of China had decreased from over 14 000 persons before the 1970s, to approximately 7000 between the 1970s and 1980s and approximately 6000 in the 1990s, and this number further declined to approximately 2000 in the 21st century (figure 1(*b*) and figure 2(*a*)). By economic region, the West contributed approximately half (49.1%) of the accumulated total annual fatalities between 1978 and 2015, which was followed by the Central (29.6%), where the more economically developed East has the lowest share. Fatality decreasing trends are consistent ($p < 0.001$), but the rate of change varies between 1978 and 2015, in each of the economic regions, with absolute fatalities declining by 67.0%, 86.7% and 80.2%, in the West, Central and East, respectively, in the 2010s compared with the 1980s (figure 2(*a*)).

In contrast with the decreasing trend of fatalities, the reported DELs from climate-related disasters show a significant increasing trend ($p < 0.001$) during 1978–2015 in China (1.7% per year during 1978–2015 and 1.3% per year since 1990, bar in figure 1(*c*)), and the DELs increased by US\$ 1 billion per year. Decadal average annual DELs (figure 1(*b*)) has increased significantly, from 24 billion (US\$) in the 1980s, to 45∼47 billion in the 1990s and an alarming 64 billion for the years in the 2010s by far (figure 2(*c*)). In regional distribution, the Central, East and West regions accounted for 35.9%, 35.2% and 28.9%, respectively, of the accumulated total annual DELs from 1990 to 2015.

While the DELs changes varied notably among the three economic regions, the West has seen the most rapid increase. Comparing the DELs (figure 2(*c*)) between the 1990s and 2010s, the West differed by a factor of 2.3, whereas the East only showed a minor increase with a factor of 1.3. Statistically, the West economic region showed a significant upward trend ($p < 0.001$), similar trend was not statistically significant for the Central ($p = 0.770$) and East ($p = 0.359$) over the same period (figure 2(*c*)).

Overall, the climate related disaster impact data from 1978–2015 in China has shown an increase of DELs (with average annual rate of 1.7%) and a decline of life loss (with an average annual rate of 5.8%). These overall trends reconfirm general observations around the world in relation to development, that is, with economic development, the per disaster event life loss tends to decrease while the DELs tends to increase (Hallegatte *et al* 2017, Hallegatte 2017). In other words, with economic development, climate-related disaster is becoming less deadly but more expensive.

Since the open and economic reform period in the late 1970s, China has seen transformative socioeconomic changes over the recent decades, with an average annual national GDP growth rate of 9.4% between 1978 and 2015 (figure 1(*c*)). The total disaster DELs reported in this period showed a significant ($p < 0.001$) correlation with the national GDP ($R^2 = 0.664$). Linking to the changing vulnerability, we next explore in detail

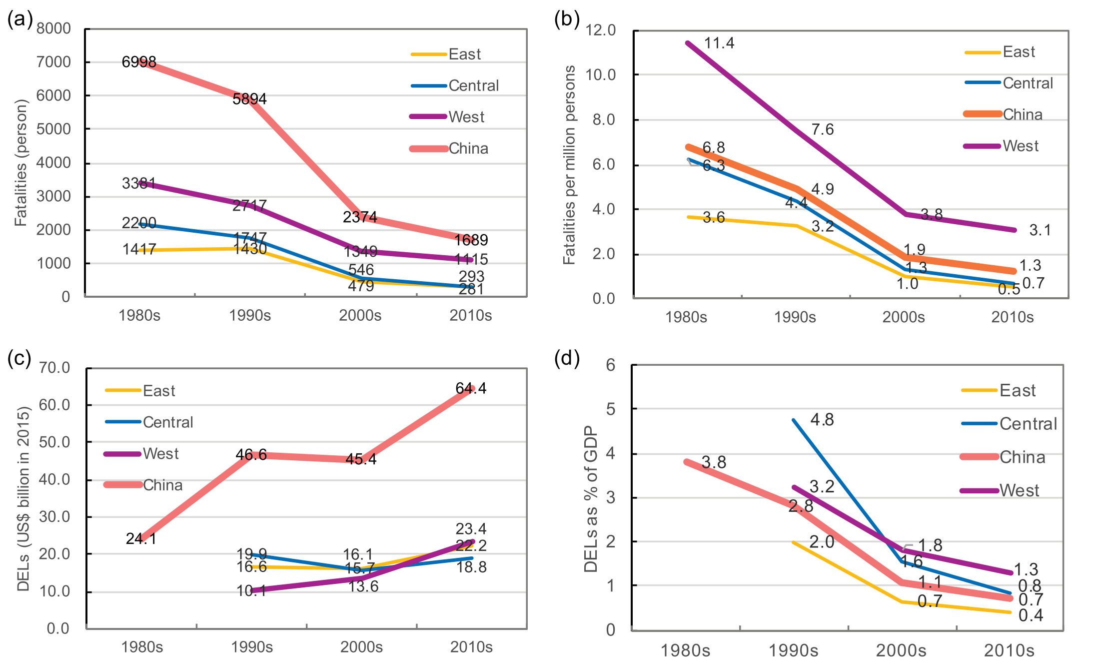

Figure 2. Decadal variability of absolute (*a*) and (*c*) and relative (*b*) and (*d*) climate-related disaster fatalities (*a*) and (*b*) and DELs (*c*) and (*d*) by region. Data source is the same as figure 1. 2010s represents the period from 2010–2015.

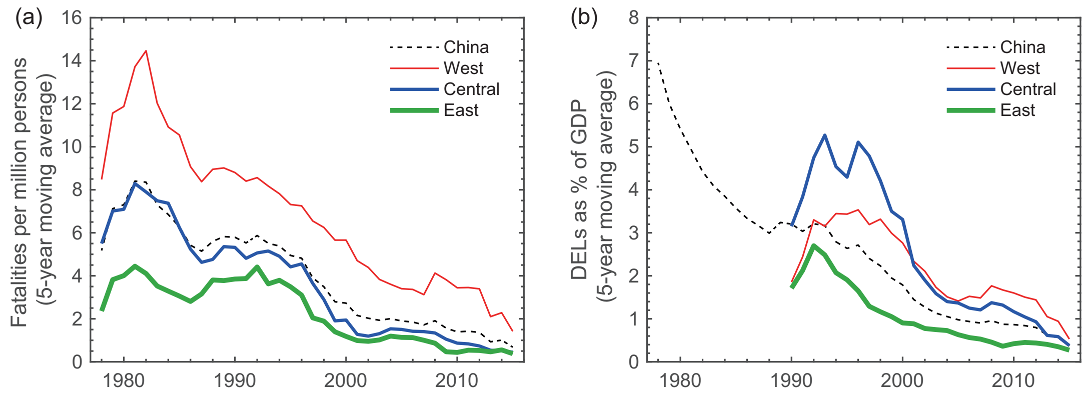

Figure 3. Temporal changes in the mortality rate (*a*) and direct economic loss rate (*b*) in the West, Central and East economic regions of China. A 5 year moving average is shown. (*a*) and (*b*) show that over recent decades, the population and GDP vulnerability to climate-related hazards have declined for each region.

the relationship between vulnerability reduction and economic development in China as a whole as well as among the economic regions in China.

3.2. Spatiotemporal characteristics of the trends and patterns in vulnerability

The results presented in figures 3(*a*) and (*b*) show that the overall national vulnerability to climate-related natural disasters declined significantly ($p < 0.001$) over the period from 1990–2015. At the national scale, the 5 year moving average of the mortality rate (the ratio of reported fatalities to the total population) and the DELs rate (percent of reported DELs to GDP) both show significant ($p < 0.001$) declining trends over the period from 1978–2015 (figures 3(*a*) and (*b*)), and the decadal average mortality rate and DELs rate declined by 74.4% and 74.1%, respectively, from the 1990s–2010s (figures 2(*b*) and (*d*)). At the regional level, this declining trend is also significant ($p < 0.001$) for the West, Central and East regions for both the mortality rate and DELs rate. The mortality rate decreased by 59.5%, 84.2% and 84.5% from the 1980s–2010s for the West, Central and East, respectively (figure 2(*b*)). The mortality rate is higher in regions with a lower income level (i.e. in the West) and lower in regions with higher income levels (i.e. in the East) (figure 3(*a*)).

The DELs rate is higher in the middle-income region, i.e. Central China, before 2006 (figure 3(*b*)), it is higher in the West region after 2006, with the DELs rate decreasing by 60.3%, 82.4% and 79.5% from the 1990s–2010s for the West, Central and East regions, respectively (figure 2(*d*)). Furthermore, a trend of

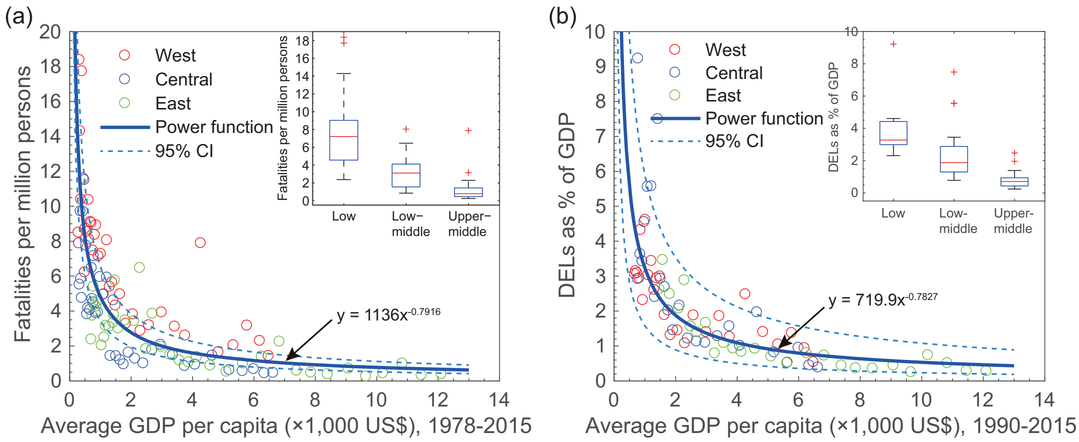

Figure 4. Relationship between income increases and declining vulnerability to climate-related disasters in China. (*a*) Relationship between GDP per capita (US$ in 2015) and mortality rate. (*b*) Same as (*a*) but for direct economic loss rate. GDP per capita increases are inversely correlated with decreased vulnerability for population (*a*) and GDP (*b*), showing a remarkable statistical power function relationship between GDP per capita and vulnerability. The distribution of mortality rates and DELs rates by income level is shown in the upper right corner of (*a*) and (*b*), respectively.

Table 1. Climate related disaster life and direct economic loss rates by income levels in China.

Income-level[a]	Per capita GDP (US$)	Disaster mortality rate (1978–2015) (per million population)		Direct economic loss rate (1990–2015) (% to GDP)	
		Range	Median	Range	Median
Low	<1025	2.4 ~ 18.4	7.1	2.3% ~ 9.2%	3.3%
Low-middle	1026–4035	0.8 ~ 8.0	3.1	0.8% ~ 7.5%	1.9%
Upper-middle	4036—12 475	0.2 ~ 2.3	0.7	0.2% ~ 2.5%	0.7%

[a] Income level classification is based on the World Bank criteria in 2015.

relative convergence of vulnerability (mortality rate and DELs rate) among the West, Central and East regions is observed from 1990–2015 (figure 3). To quantitatively demonstrate how income level co-relates with vulnerability, we fitted the income and vulnerability data as shown in figure 4.

The results clearly show a strong negative non-linear (power function) relationship between income (GDP per capita) and mortality rates for the period from 1978–2015 (figure 4(*a*)), and between income (GDP per capita) and direct economic loss rate from 1990–2015 (figure 4(*b*)). To further illustrate this co-relation, we grouped the income levels into Low, Low-middle and Upper-middle according to the World Bank classification criteria in 2015 (table 1).

There are notable differences on the DELs rates between income levels. It seems that there is a possible income level threshold (around 4000US$ per capita GDP) above which we see rather significant vulnerability reduction in terms of disaster mortality and DELs rates.

Regionally, there are substantial differences of overall vulnerability among the economic regions—West, Central and East (figure 4). Take the 2010s as example, with a national average –about 1.3 for morality rate and 0.7% for DELs rate (figures 2(*b*) and (*d*)), the West and East regions differ by a factor of 6 (3.1/0.5, mortality rate) and 3 (1.3/0.4, DELs rate) (figures 2(*b*) and (*d*)). Such difference is highly correlated to the overall income levels of the different economic regions with the East's per capita GDP is approximately two times of the West (figure 4).

4. Discussions

In this study, we investigated the spatial heterogeneity of climate-related natural disaster vulnerability trends and further detected its relationship with economic development across the West, Central and East economic regions in mainland China. We found that the economic development level is correlated with the vulnerability change magnitude, and there was a distinct vulnerability change response to the economic development level.

4.1. Prominent decrease in human and economic vulnerability to climate-related disasters in China

Previous studies have observed an inverted U-shaped relationship between economic development (per capita GDP) and DELs rate on a national scale for natural disasters as a whole (Kellenberg and Mobarak 2008, Zhou *et al* 2014). However, clear evidence of such a pattern for climate-related natural disaster vulnerability is not observed in any of the aggregated economic regions in this study, which is consistent with other climate-related natural disaster studies described above (Kahn 2005, Jongman *et al* 2015,

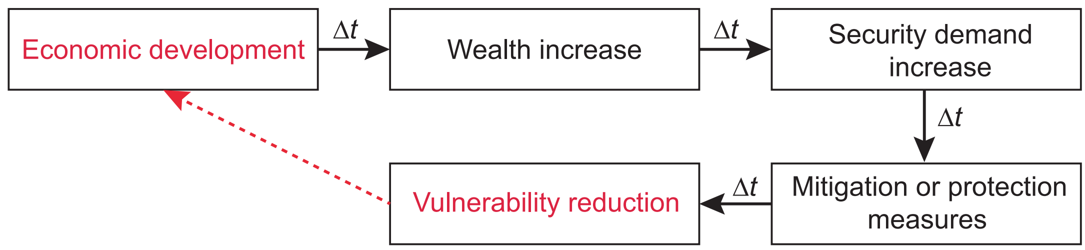

Figure 5. Potential links between economic development and vulnerability reduction (Δt denotes time-lag) for climate-related disasters.

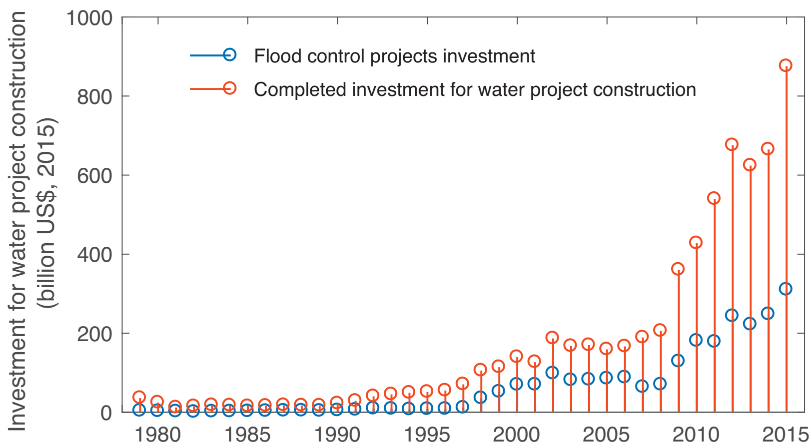

Figure 6. Annual investment for water project construction from 1978–2015 in China (data source: MWR 2016). Investment series were adjusted to the 2015 year price level using CPI.

Georgeson *et al* 2017, Ward and Shively 2017). Our results show a general pattern of decreasing vulnerability over time within all economic regions and a clear vulnerability gap between them. Importantly, the vulnerability declined non-linearly with per capita GDP.

Economic development-induced security demand should be an important driver for vulnerability reduction activities (figure 5). With rapid urbanization and economic growth since 1978, the value of assets and population at risk of climate-related natural disaster has escalated (Qin *et al* 2015), major climate-related disasters and their impacts have forced the government to pursue effective new strategies to reduce disaster risk and to reduce vulnerability. Taking Chinese flood disaster management as an example, the government started to focus on essential engineering measures in the 1990s, including the construction of both the Three Gorges Dam in the upper Yangtze River and the Xiaolangdi Water Control Project in the Yellow River. In 1994, the Standard for Flood Control (GB 50201–94) was approved, and a Flood Control Law was passed in 1997. Finally, Chinese average annual flood control investment had increased from 2.6 billion US$ in the 1980s, to 15.0 billion US$ in the 1990s, and to 83.5 billion US$ in the 2000s and further to 203.2 billion US$ in the 2010s (2010–2015) (figure 6), especially in the 2000s, this investment accounted for 46.4% of the annual gross investment for water project construction on average. For non-engineering measures, China issued a national emergency plan for natural disasters in 2006, and the government began to seek a balanced approach using both structural and nonstructural measures to reduce disaster risk.

Overall, from the supply-demand relationship perspective, increases in income increase the demand for safety, and a higher income enables individuals to employ costly precautionary engineering and non-engineering measures in response to this demand (Toya and Skidmore 2007). Evidently, richer regions are better able to agree upon, invest in, and implement zoning regulations, building codes, early warning systems, emergency response systems and other measures that reduce natural disaster risk and mitigate the consequence of natural disasters (Ferreira *et al* 2013, Park *et al* 2015, Hallegatte *et al* 2017). Which should be the causal link between economic growth and vulnerability reduction, but it is extremely hard to quantify such relationship due to the difficulty in attribution since many other factors involved in shaping the vulnerability that is highly context specific (Cutter and Finch 2008).

4.2. The rationale for analyzing the sub-country scale relationship between economic development and climate-related natural disaster impact

Generally, studies that statistically analyze the relationship between natural disasters and economic development have focused on the worldwide scale and largely depend on the available global disaster loss datasets, i.e. the EM-DAT from CRED (Anbarci *et al* 2005, Kahn 2005, Rashky 2008, Kellenberg and Mobarak 2008, Schumacher and Strobl 2011, Tanoue *et al* 2016). However, these worldwide or cross-country analyses were based on natural disaster records combining a large number of countries, country clustering reduces the bias of the tests of statistical significance on standard errors but tend to overstate the significance of explanatory variables (Ferreira *et al* 2013). Therefore, these analyses do not represent a true dynamic study of the relationship between economic development and disaster vulnerability in any particular country. Meanwhile, although EM-DAT is widely used in these studies, EM-DAT has the shortcoming of underreporting smaller natural disaster events, especially, in developing countries (Jonkman 2005). Because there is high spatial disparity in economic growth from the west to the east in China, a sub-national level analysis of the complex dynamic relationships between economic development and climate-related disasters in China is helpful to obtain insights into the necessity of adaption strategies, especially in undeveloped regions.

On the other hand, hazard frequency is an important driver that affects the annual disaster losses and increases the variance in human and direct economic loss rates for each province, therefore, this study performing the analysis at the economic region (or zone) scale helps eliminate this variance generated by differences in hazard frequency as climate-related hazard frequencies are more uniform inter-annually in the economic region scale rather than in province scale, thus, the relationship among factors is more robust in economic region scale than in province scale theoretically.

4.3. Conceptual challenges associated with measuring the causal relation between economic growth and climate-related disaster vulnerability

The current paper attempts to add a subnational empirical study that maps the co-relationship and pattern between economic development and the vulnerability to climate-related disasters. While we have identified a statistically significant co-relationship between the economic development and vulnerability to climate related disasters, this co-relationship should not be taken as or confused with any claim on the causal relationship between the two. While qualitatively there are surely causal linkages between the two, quantifying such causal 'attribution' is challenging both conceptually and methodologically. First, the economic growth itself can be affected by disasters, yet quantifying those effects are difficult. Using the global disaster database, Cavallo and colleagues (Cavallo *et al* 2013) examined the relationship between catastrophic natural disasters and economic growth. They have concluded that only extremely large disasters have a negative effect on output in both the short and the long runs. At the same time, no significant effect on economic growth has been detected once political changes were controlled.

On the other hand, the impact of climate change on both economic growth as well as the pattern of climate-related hazards would also have profound impacts on the relationship between economic growth and vulnerability to climate-related disasters. Burke *et al* (2015) have found a representative concave-type non-linear effect of temperature on economic production in both poor and rich countries, and technological advances or the accumulation of wealth and experience since 1960 did not fundamentally altered this non-linear relationship between productivity and temperature. Hsiang *et al* (2017) further developed a new integrated architecture to report updated climate change damage based on a notable improvement in econometrically derived dose-response functions that reflect the non-linear effects of temperature to climate cost via Bayesian meta-analysis in the United States.

Furthermore, the causal relationship between economic development and vulnerability is a complex balance of increasing exposure (more to lose) and enhanced adaptive capacity (more to invest). Yet, our knowledge on estimating the feasibility and cost of adaptive responses to climatological processes remains limited (Hsiang and Narita 2012, Fraser *et al* 2013).

4.4. Some limitations of this study

Some limitations exist in our study. First, improved disaster reporting arising out of better information and communications technology can affect data on disaster impacts records. Disaster impacts usually could be systematically underreported in poorer regions and in early decades, as Zhang *et al* (2009) indicated that natural disaster impacts records prior to the early 1990s in China are considered incomplete for the description of the spatiotemporal patterns at the provincial or a lower scale, which is also one of the reasons for economic region scale analysis (in this study) but not province scale. Even after the reporting biases are adjusted (i.e. the yearly deaths were rising in poor provinces before 1990s), the declining trend of deaths and mortality rate with per capita GDP are still not change. While for DELs, we used the disaster impact data series from 1990–2015 directly to avoid this reporting bias. Anyway, compared with lots of missing disaster impact records of EM-DAT for Chinese regions, especially for early years, the published statistical disaster impacts data from Chinese government agencies (as we used above) should be a beneficial supplement to better reflect the regional disparity of disaster impacts.

Second, because we did not distinguish between sub-type climate-related disasters, there is a gap between the real exposure and the administrative population or GDP used in this paper. Extracting the real exposure to each disaster type as performed in other related studies (e.g. Jongman *et al* 2015) is difficult because of the absence of information on the exact location of the reported fatalities and DELs and the corresponding disaster types, therefore, using accumulated provincial total population or GDP to represent economic zone exposure will inevitably exaggerate the actual exposed population or GDP if the occurrence of multiple climate-related disaster events at the same province in the same year is not accounted for. As such, the non-linear relationship between per capita GDP and vulnerability should be taken with care. Further studies using a certain disaster type and high-resolution modelling of exposure via asset value map (Wu *et al* 2018) to explore this non-linear relationship is of great value for reducing this uncertainty (e.g. Jongman *et al* 2015, Geiger *et al* 2016).

Finally, as a developing country, economic development in most of China's provinces still does not reach a high-income level, therefore, how vulnerability will change with economic development in the future will depend on how effective disaster risk reduction measures are implemented now.

5. Conclusions

Based on data from the West, Central and East economic region across mainland China, our study found that the trends in climate-related human and direct economic losses vary with different levels of economic development. Among them, absolute fatalities, the mortality and direct economic loss rates showed a significant declining trend in China overall as well as in the East, Central and West regions. The convergence of vulnerability trends in the regions with different economic development in recent decades is obvious, whereas absolute direct economic losses mainly show upward trends in relatively underdeveloped regions (i.e. the West). We further demonstrated that human and economic vulnerability to climate-related disasters is highly related to economic development level, both mortality rates and direct economic loss rates decreased with income increase across China. These findings also emphasize that human behavior in determining the difference between a hazard and a disaster and provide much needed insights in human and economic vulnerability to climate-related disaster impacts, although higher income does not necessarily lead to a better protection or preparation against climate-related disasters.

Notwithstanding the above, the findings of the paper contribute to advancing the knowledge on the economic development-vulnerability links and help stimulating further discussion and analysis. The paper suggests a focus not only on the exposure effects of economic growth but also on the implications of economic development on adaptation capacity, i.e. economic growth can offer opportunities for disaster risk management, such as designing and financing efficient adaptation strategies as observed in China.

Further analysis is needed on the quantitative relation between economic development and vulnerability. First, more causal factors of vulnerability should be introduced to establish the link with status of different risk management policies and adaptation measures in different economic development regions, focusing in particular on their inherent feedbacks but also trade-offs and conflicts. Then, more detailed studies are required to determine the relationship between vulnerability and observed losses trend combined with hazard level and exposure for a sub-type (e.g. cyclone) climate-related disaster (e.g. Ashley and Strader 2016, Fricker *et al* 2017). Finally, as most climate change impacts assessment models were criticized for lacking a strong empirical basis for their damage functions (Moore and Diaz 2015). It is of critical value to construct empirically-derived climate damage functions based on the climate-related disaster impacts combined with local temperature change, such as the innovative works from Burke *et al* (2015) and Hsiang *et al* (2017) who found that climate change damage is nonlinear to warming. Overall, the economic development-vulnerability pattern might prove helpful for profiling vulnerability assessments and integrated assessment models when exploring potential pathways of climate change vulnerability under the shared socio-economic pathways. Increased efforts will be needed to further explore and deepen our understanding of economic development- climate vulnerability relationship as well as their characteristics across different regions.

Acknowledgments

This work was supported by the National Key Research and Development Program—Global Change and Mitigation Project: Global change risk of population and economic system: mechanism and assessment (2016YFA0602403), National Natural Science Foundation of China (41571492), and the 111 Project 'Hazard and Risk Science Base at Beijing Normal University' under Grant No. B08008. The authors are also grateful to the three anonymous reviewers for their very valuable comments on an earlier version of this manuscript.

ORCID iDs

Jidong Wu https://orcid.org/0000-0001-8208-8373

References

Adger W N 2006 Vulnerability *Glob. Environ. Change* **16** 268–81

Anbarci N, Escaleras M and Register C A 2005 Earthquake fatalities: the interaction of nature and political economy *J. Public Econ.* **89** 1907–33

Anttila-Hughes J K and Hsiang S M 2013 *Destruction, Disinvestment, and Death: Economic and Human Losses Following Environmental Disaster* (https://doi.org/10.2139/ssrn.2220501)

Ashley W and Strader S 2016 Recipe for disaster: how the dynamic ingredients of risk and exposure are changing the tornado disaster landscape *Bull. Am. Meteorol. Soc.* **97** 767–86

Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* 527 235–39

Cavallo E, Galiani S, Noy I and Pantano J 2013 Catastrophic natural disasters and economic growth *Rev. Econ. Stat.* 95 1549–61

Coburn A W, Spence R J S and Pomonis A 1994 *Vulnerability and Risk Assessment* (UNDP Disaster Management Training Program) (Cambridge, UK: Cambridge Architectural Research)

Cutter S L and Finch C 2008 Temporal and spatial changes in social vulnerability to natural hazards *Proc. Natl Acad. Sci.* 105 2301–06

Fankhauser S and McDermott T K J 2014 Understanding the adaptation deficit: why are poor countries more vulnerable to climate events than rich countries? *Glob. Environ. Change* 27 9–18

Ferreira S, Hamilton K and Vincent J R 2013 Does development reduce fatalities from natural disasters? New evidence for floods *Environ. Dev. Econ.* 18 649–79

Fraser E D G, Simelton E, Termansen M, Gosling S N and South A 2013 'Vulnerability hotspots': integrating socioeconomic and hydrological models to identify where cereal production may decline in the future due to climate change induced drought *Agric. Forest Meteorol.* 170 195–205

Fricker T, Elsner J B and Jagger T H 2017 Population and energy elasticity of tornado casualties *Geophys. Res. Lett.* 44 3941–49

Garschagen M and Romero-Lankao P 2015 Exploring the relationships between urbanization trends and climate change vulnerability *Clim. Change* 133 37–52

Geiger T, Frieler K and Levermann A 2016 High-income does not protect against hurricane losses *Environ. Res. Lett.* 11 084012

Georgeson L, Maslin M and Poessinouw M 2017 Global disparity in the supply of commercial weather and climate information services *Sci. Adv.* 3 e1602632

Hallegatte S 2017 A normative exploration of the link between development, economic growth, and natural risk *Econ. Disasters Clim. Change* 1 5–31

Hallegatte S, Green C H, Nicholls R J and Corfee-Morlot J 2013 Future flood losses in major coastal cities *Nat. Clim. Change* 3 802–06

Hallegatte S, Vogt-Schilb A, Bangalore M and Rozenberg J 2017 *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters* (Washington, DC: Climate Change and Development, World Bank)

Hsiang S *et al* 2017 Estimating economic damage from climate change in the United States *Science* 356 1362–69

Hsiang S M and Jina A S 2013 *The causal effect of environmental catastrophe on long-run economic growth: evidence from 6700 cyclones* (NBER Working paper No. 20352 https://doi.org/10.3386/w20352)

Hsiang S M and Narita D 2012 Adaptation to cyclone risk: evidence from the global cross-section *Clim. Change Econ.* 3 1250011

Huang G 2014 Does a Kuznets curve apply to flood fatality? A holistic study for China and Japan *Nat. Hazards* 71 2029–42

IPCC (Intergovernmental Panel on Climate Change, Climate Change) 2001 *Impacts, Adaptation and Vulnerability* ed J McCarthy, O Caniziani, N Leary, D Dokken and K White (Cambridge: Cambridge University Press) pp 451–486 ch 9

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 IPCC* ed C B Field *et al* (New York: Cambridge University Press)

Jonkman S N 2005 Global perspectives on loss of human life caused by floods *Nat. Hazards* 34 151–75

Jongman B, Winsemius H C, Aerts J C, de Perez E C, van Aalst M K, Kron W and Ward P J 2015 Declining vulnerability to river floods and the global benefits of adaptation *Proc. Natl Acad. Sci.* 112 E2271–80

Kahn M E 2005 The death toll from natural disasters: the role of income, geography and institutions *Rev. Econ. Stat.* 87 271–84

Kellenberg D and Mobarak A 2008 Does rising income increase or decrease damage risk from natural disasters? *J. Urban Econ.* 63 788–802

Klompa J and Valckx K 2014 Natural disasters and economic growth: a meta-analysis *Glob. Environ. Change* 26 183–95

Koks E E, Jongman B, Husby T G and Botzen W J W 2015 Combining hazard, exposure and social vulnerability to provide lessons for flood risk management *Environ. Sci. Policy* 47 42–52

MHURD (Chinese Ministry of Housing and Urban–Rural Development) 2015 *China Urban Construction Statistical Yearbook 2014* (Beijing: China Statistics Press)

Mills E 2005 Insurance in a climate of change *Science* 309 1040–44

Moore F C and Diaz D B 2015 Temperature impacts on economic growth warrant stringent mitigation policy *Nat. Clim. Change* 5 127–31

MWR (Ministry of Water Resources) 2016 *China Water Statistical Yearbook 2016* (Beijing: China Water & Power Press)

Padli J, Habibullah M S and Baharom A H 2010 Economic impact of natural disasters' fatalities *Int. J. Soc. Econ.* 37 429–41

Park D S R, Ho C H, Nam C C and Kim H S 2015 Evidence of reduced vulnerability to tropical cyclones in the Republic of Korea *Environ. Res. Lett.* 10 054003

Peduzzi P, Chatenoux B, Dao H, De Bono A, Herold C, Kossin J, Mouton F and Nordbeck O 2012 Global trends in tropical cyclone risk *Nat. Clim. Change* 2 289–94

Qin D H, Zhang J Y, Shan C C and Song L C 2015 *China National Assessment Report on Risk Management and Adaptation of Climate Extremes and Disasters* (Beijing: Refined Edition, Science Press)

Rashky P 2008 Institutions and the losses from natural disasters *Nat. Hazards Earth Syst. Sci.* 8 627–34

Schumacher I and Strobl E 2011 Economic development and losses due to natural disasters: the role of hazard exposure *Ecol. Econ.* 72 97–105

Simelton E, Fraser E D G, Termansen M, Forster P M and Dougill A J 2009 Typologies of crop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961–2001) *Environ. Sci. Policy* 12 438–52

SSTCND (State Scientific and Technological Commission of Major Natural Disasters) 1994 *China Major Natural Disasters and its Mitigation Measures* (Pandect, Beijing: Science Press)

Tanoue M, Hirabayashi Y and Ikeuchi H 2016 Global-scale river flood vulnerability in the last 50 years *Sci. Rep.* 6 36021

Toya H and Skidmore M 2007 Economic development and the impacts of natural disasters *Econ. Lett.* 94 20–5

UNISDR (United Nations International Strategy for Disaster Reduction) 2017 *UNISDR Terminology on Disaster Risk Reduction 2017*

Ward P S and Shively G E 2017 Disaster risk, social vulnerability, and economic development *Disasters* 41 324–41

WMO (World Meteorological Organization) 2014 *Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2012)* (WMO, WMO-No. 1123) (http://library.wmo.int/pmb_ged/wmo_1123_en.pdf)

Wu J, Fu Y, Zhang J and Li N 2014 Meteorological disaster trend analysis in China: 1949–2013 *J. Nat. Resour.* 29 1520–30

Wu J, Li Y, Li N and Shi P 2018 Development of an asset value map for disaster risk assessment in china by spatial disaggregation using ancillary remote sensing data *Risk Anal.* 38 17–30

Wu J, Wang C, He X, Wang X and Li N 2017 Spatiotemporal changes in both asset value and GDP associated with seismic exposure in China in the context of rapid economic growth from 1990–2010 *Environ. Res. Lett.* 12 034002

Zhang Q, Wu L and Liu Q 2009 Tropical cyclone damages in China 1983–2006 *Bull. Am. Meteorol. Soc.* 90 489–95

Zhou Y, Li N, Wu W, Liu H, Wang L, Liu G and Wu J 2014 Socioeconomic development and the impact of natural disasters: some empirical evidences from China *Nat. Hazards* 74 541–54