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University of Hamburg
Research Group Climate Change and Security

Working Paper
CLISEC-27

Climate-related Flood Risks and Urban Responses in the Pearl River Delta, China*

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Abstract

Growing concern on climate-related flood hazards has led to increasing interest in understanding the interactions of climate, flood and human responses. This paper jointly investigates climate change trends, impacts on flood events, flood vulnerability and risk, and response strategies in the Pearl River Delta (PRD), a rapidly urbanizing area in the southeast coast of China. Own analysis based on a reanalysis dataset and model projections are integrated with results in the literature, which indicates a climate scenario of increasing mean temperature, precipitation, sea level and typhoon intensity, as well as the frequency of extreme weather events in the PRD. These trends, together with the continuing urbanization in flood-prone areas, are expected to increase flood frequency and aggravate both the scale and degree of flooding in most of the cities in PRD. We further estimate the vulnerability to flood in the 11 PRD cities using the indicator system method. The results suggest that the exposure and sensitivity of central cities (Hong Kong, Macao, Shenzhen and Guangzhou) are very high because of highly exposed populations and assets located in lowland areas. However, the potential vulnerability and risk can be low due to high adaptive capacities (both by hard and soft flood-control measures). A novel framework on flood responses is proposed to identify vulnerable links and response strategies in different phases of a flood event. It further suggests that the flood risks can be mitigated by developing an integrated climate response strategy, releasing accurate early warning and action guidance, sharing flood related information to the public and applying the advantages of online social network analysis.

Keywords: Climate change impact; Flood hazard; Vulnerability; Response strategy; Adaptation; Pearl River Delta

1 Introduction

Climate change and the potential impacts are extensive (Adger et al. 2003), posing one of the greatest environmental, economic and security challenges the world is facing (Martens et al.

* A shortened version of this paper has been submitted to the journal *Regional Environmental Change*.

2009; Scheffran and Battaglini 2011). Cities, as the concentrated representation of human society, are identified among the most vulnerable regions in the context of climate change (Stern 2007; IPCC 2007a). In addition, many urban areas around the world, especially in developing countries, are developing rapidly with obvious population growth and asset accumulation, which further exacerbates the vulnerability of cities to climate-related hazards like floods (Lebel et al. 2011; Mirza 2011). However, the interactions between climate change, flood hazard and social responses are not yet clear, especially at the local scale in developing areas, because of limits of methodology and lack of integration.

Currently, global and regional climate models (GCMs & RCMs) are the mainstream for climate projection. While GCMs are ineffective for skillful climate forecasting at regional scale due to low resolution (IPCC 2007b), RCMs call for detailed local data input (Christensen et al. 2007) which is often not available in developing areas. Further considering the limitations on our knowledge of how the climate system works, different climate models may have different abilities and can give different projections (Hurk et al. 2013). Observation and statistical data are usually used to produce specific information when focusing on the area of interest. However, a gap exists between climate model and observation-based statistic analysis (Wood et al. 2004), which in fact indicates a hard task to integrate climate simulation and local situations.

Flood hazard projections under climate change are typically derived by hydrological models with inputs generated from climate models (Delgado et al. 2013), regardless of the uncertainties in models. This suggests a combination of the climate system and local hydrological situation. With this principle, existing literature explores flood risk based on hydrological models (Alfieri et al. 2013; Arduino et al. 2005; Bell et al. 2007), which actually presents mostly the probability of flood occurrence from the nature side. Indeed, there is further potential for flood risk to increase in frequency and intensity due to the vulnerable social situations of the case area (Balica et al. 2012; IPCC 2012). Especially in a developing area, social differences are fairly greater than environmental differences. The regional hydrological model may support a reliable flood situation of an area (Mujumdar and Kumar 2013) but hardly demonstrates the variant local strategies and activities in flood prevention and response. Therefore, integration of both the hydrological situation and social vulnerability would support a comprehensive understanding of flood risk in a regional case. Furthermore, effective response measures are also vital in reducing flood consequences and severity (Naess et al. 2005), and should therefore be considered thoroughly in a comprehensive flood analysis.

Due to broad application in multiple disciplines, there are different meanings of the terms vulnerability and risk (Wolf 2012). However, the International Panel on Climate Change (IPCC) has clear definitions for these and other related terms in the climate and disaster communities: disaster risk derives from a combination of physical hazards and the vulnerabilities of exposed elements (IPCC 2012); vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC 2007a). Although several studies improved the IPCC definition with vulnerable components classification (Balica et al. 2012), spatial-temporal dynamics (Sahin and Mohamed 2013) and practicability (Coletti et al. 2013), the principal idea is still preserved. However, vulnerability assessment alone is not able to support information on probability, degree or extent of a disaster risk. Thus there is an urgent need to integrate local vulnerability into disaster risk assessment with concern of climate change impacts.

This paper contributes to the emerging field of climate-related flood risk in coastal urban areas by identifying the climate change trends and associated flood probability, assessing the vulnerability to flood and discussing the appropriate response strategies in the Pearl River Delta (PRD) in southern China. Two major advances of this paper are: integrating the results of climate modeling and observation-based statistic analysis to get reliable results; emphasizing detailed social-economic information on the basis of the regional hydrological situation for flood risk analysis. In doing so, we first compare the findings about climate change trends in different sources. The paper then focuses on changes in the main causes of urban flooding and describes the potential changes in flood probability, followed by a section of a comprehensive assessment on the vulnerability of the PRD cities. These enable us to identify both the climate impacts which are most likely to trigger a flood occurrence and the vulnerability of this metropolitan area which highlights the weak links in flood responses. Finally we create a framework that integrates the flood risk elements with their corresponding pathways and response measures in section 5. The paper concludes by discussing the key insights observed in analyzing the climate-impact-risk link for PRD, along with a suggested approach to facilitate the implementation of phase-based measures.

2 Study area and methodology

2.1 Study area

The Pearl River Delta (PRD) is located at the mid-south part of Guangdong Province in Southern China (Figure 1), and is formed as a 42657 km^2 sedimentary plain of the Pearl River with its three branches, namely West River, North River and East River. The PRD is dominated by a sub-tropical monsoon climate with abundant precipitation. The long term annual mean precipitation is around 1800 mm and about 85% of precipitation occurs during April to September. The topography of the PRD has mixed features of crisscrossing river networks, channels, shoals and river mouths (gates). Annually average discharge to the sea reaches 325.9 billion m^3, including 80% from the West River. Water flow at the estuary is influenced by both the river runoff and sea tide, with water level variation between 0.86-1.63m in a half-day return period.

Comprising of 60.8 million inhabitants in 2010, the PRD is in rapid urbanization and is now among the most prosperous metropolitan areas around the world. The GDP of the PRD cities reaches 791.1 billion US$ in 2010 with an average annual rate of 16.2% in the last decade. This rapid development is accompanied with intensified land use change, e.g. built-up areas increased from 4.14% in 1988 to 20.61% in 2008 (Ye et al. 2012), and is still continuing with positive prospects for the future. For about 30 years labor migration into the PRD area contributes significantly to this prosperity as well as the population expansion (23.25 million in 1982 vs 60.8 million in 2010). Although the growth rate of the population is declining, the absolute number continues to increase and would stay at a high level of about 63 million after 2020, as indicated by the Guangdong Provincial Territorial Planning (2006-2020).

The natural environment of PRD is sensitive and variable due to strong monsoon, dense river-net and significant effects of erosion and deposition. Rapid economic development and population growth have further intensified the fragmentation of the natural environment. These factors combined make the PRD prone to natural disasters, of which flood is the most serious. Although increasing hydraulic engineering (mainly reservoir and dam) in the upstream area prevent certain fluvial floods for the PRD, local extreme weather and poor drainages in the context of climate change and urbanization make the flood threat still a high concern for government and stakeholders (Peng et al. 2008; Chan et al. 2012).

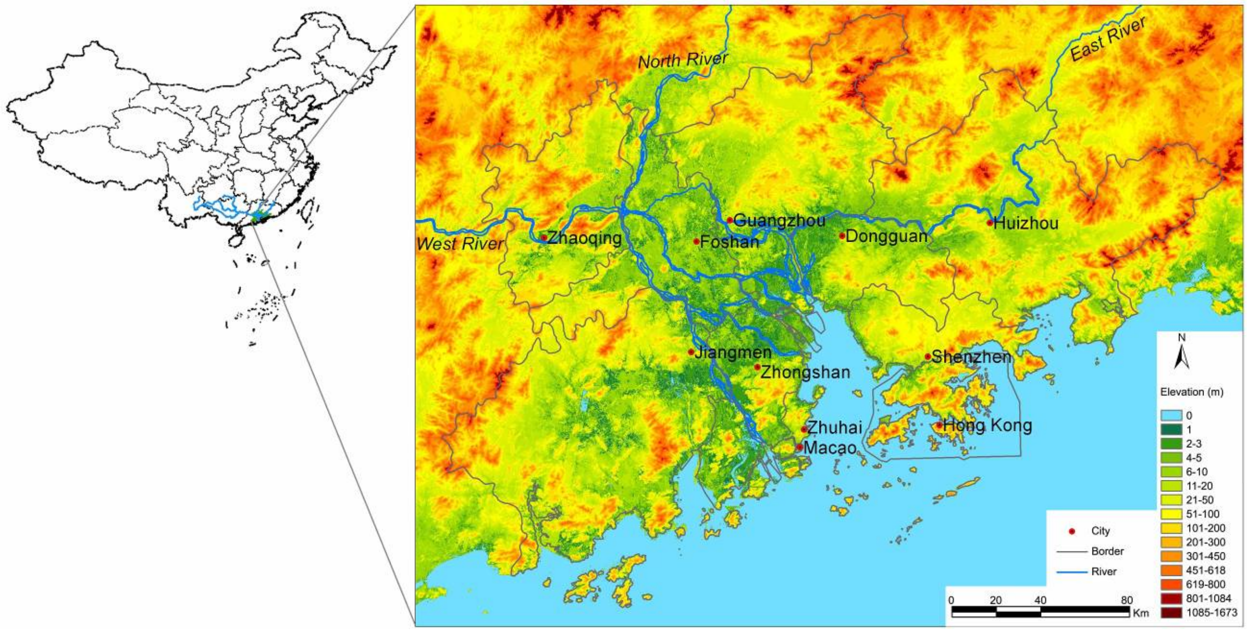

Figure 1, Map of the Pearl River Delta, showing its location, elevation, cities and the river system.

2.2 Method and data for climate change analysis

Both historical and further climate change trends in the PRD area are discussed as a background for flood analysis. To get a comprehensive view, several approaches are adopted and multiple results are integrated, instead of a single multifunctional method.

For the historical trends, linear regression is initially used to give visual trends in temperature, precipitation, sea level and typhoons and their anomalies. The Mann-Kendall trend test is applied later to statistically detect the significance of these trends. Anomalies are computed with respect to the respective average value. Fitting lines are given respectively with corresponding fitting equations and R-squared values. These data are obtained from the Hong Kong Observatory (HKO), tide gauges at Denglongshan and Hengmen, Guangdong Statistic Yearbook (2011&2012) and academic publications like He and Yang (2011) and Kong et al. (2010). In particular, the analysis of precipitation in the PRD area during 1957-2009 is based on China's Daily Terrestrial Climate Dataset in the China Meteorological Data Sharing Service System.

We present quantitative projections of the trends of changing temperature, precipitation and sea level in PRD and its surrounding areas in Guangdong Province. For temperature and precipitation from 2006 to 2100, simulations of the Max Planck Institute for Meteorology Earth Systems Model were run on low resolution (MPI-ESM-LR) within the Coupled Model Inter-comparison Project Phase 5 (CMIP5). Results are adopted under the three representative concentration pathway (RCP) scenarios: a high emission scenario (RCP8.5), a midrange mitigation emission scenario (RCP4.5), and a low emission scenario (RCP2.6). Details of the reanalysis dataset, MPI-ESM-LR and RCPs are referred to by Kalnay et al. (1996), Giorgetta et al. (2013) and Vuuren et al. (2011), respectively.

The reanalysis dataset of the National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NCEP/NCAR) is applied to analyze the annual mean temperature and precipitation (1948-2005) in Guangdong Province. We selected grid points in the NCEP/NCAR reanalysis dataset covering the whole province to represent the climate change of the study area. Then the average of annual mean temperature and precipitation of these grid points are calculated by combining unweighted locations. Finally these reanalysis-based findings (1948-2005) are combined together with the modeling results (2006-2100) to draw a long term climate change trend encompassing the past and future.

Sea level projection is more complicated. In the context of global climate warming, sea level changes are considerably related to surface temperature (Vermeer and Rahmstorf 2009; Rahmstorf 2007), in especially decadal/century or even longer time scales. Since the Pearl River estuary and even the South China Sea has no strong local processes (e.g. no additional glacier melting water), the sea level in this region reflects mainly the global ocean and climate situations. Therefore, we apply the semi-empirical approach (Vermeer and Rahmstorf 2009; Rahmstorf et al. 2012, Equation 1) to simply assess the sea level of the Pearl River estuary and its surrounding area, based on the projected temperature above:

$$dH/dt = a(T - T_0) + b \cdot dT/dt \tag{1}$$

Here, T_0 is a base temperature at which sea level is in equilibrium with climate, so that the rate of rise of sea level H, dH/dt, is proportional to the warming dT/dt above this base temperature. The a and b are coefficients to be determined by model training. Therefore, the future sea level changing can be calculated on the basis value of the year 2005 and shown comparatively together with the features during 1948-2005. Background data derives from the Hong Kong Observatory.

The Mann-Kendall test (MK-test, Mann 1945; Kendall 1975) for trend detection is applied to statistically clarify all the trends of the climate elements analyzed above, including the past and future characteristics. The MK-test is a non-parametric test that has been widely used for studying the temporal trends of climatic series (Chen et al. 2011a; Zhang et al. 2012; Bawden et al. 2014; Fiener et al. 2013; Westra et al. 2013). Since the MK-test technique is presently quite mature, there are several platforms to perform it. In this study the MK-test was conducted using the Microsoft XLSTAT 2013, with 5% significant level for all the tests.

2.3 Method and data for identifying flood risk

Flood risk emerges from the interaction of flood hazard and vulnerability (Merz et al. 2010). Empirical analysis was taken to identify the flood probability and its links to climate change. Major flood causes like rainstorms, sea level rise and human-induced factors are discussed based on historical time-series records, generally in the last ten years. This gives an empirical view of the interactions between precipitation, typhoon and flood impacts in Guangdong Province.

Data are based on empirical sources from Guangdong Statistic Yearbook (2000-2012) and Guangdong Water Resource Bulletin (2000-2011) as well as researches by Huang et al. (2000) and Chen et al. (2012). The information on human-induced hydrological changes was obtained during field research in the case area in November-December 2011 and also referred to academic literature. Elevation data for sea water inundation was derived from the ASTER GDEM (V1) which is provided by the International Scientific & Technical Data Mirror Site, the Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn).

Consistent with common usage and definitions by Adger (2006), Füssel and Klein (2006) and IPCC (2007a), the vulnerability to flood hazards (V) can be identified by its three elements: exposure (E), sensitivity (S) and adaptive capacity (Ac). To quantitatively evaluate the PRD cities' vulnerabilities in this study, we apply the method of vulnerability indicator system, used and suggested by many researchers (Xie et al. 2008; McLaughlin and Cooper 2010; Balica et al. 2012). A total of 15 indicators are sorted into three parts according to each elements (Table 1).

In the evaluation, each original value $x_{i,j}$ for the indicator *i* of the city *j* was firstly converted into a normalized dimensionless number $NI_{i,j}$ (on a scale from 0 to 1) using the method of min-max normalization (Equation 2, Karmakar et al. 2010), where the max_i and min_i represent the maximum value and minimum value of the given indicator in the 11 cities. We then assume that the indicators share equal weights in each of the three elements and calculate the arithmetical mean as the index of E, S and Ac, respectively. Finally, the integrated vulnerability index is assessed by the addition and subtraction function V=E+S-Ac (Cutter and Finch 2008; Cardona 2007; Balica and Wright 2010).

$$NI_{i,j} = \frac{x_{i,j} - \min_i}{\max_i - \min_i} \tag{2}$$

Primary data for vulnerability assessment was collected from the Statistical Yearbooks of Guangdong Province (2002-2011), statistical yearbooks of each city (2002-2011), the sixth census of each city (2010, except Hong Kong and Macau), government publications and news reports in related cities in 2010. It has to be mentioned that a few indicator values (e.g. economic sector and drainage system) are not exactly comparable due to different statistical criteria of these cities.

Table 1. Indicator system for flood vulnerability evaluation

Element	Indicator	Definition	Function
Exposure (E)	Land elevation	Ratio of low-land area (<= 3m above the sea level)	+
	River system	River-net density defined as river length divided by land area	+
	Precipitation	Average of the annual precipitations (2002-2011)	+
	Urbanization	Urbanization level (the proportion of urban population)	+
	Built-up area	Ratio of built-up area in the city	+
Sensitivity (S)	Population density	Population per km^2	+
	Road density	Average length of roads per km^2	+
	Sensitive Population	Ratio of population less than 15 and elder than 65 years old	+
	Economic density	Gross Domestic Production (GDP) per km^2	+
	Economic sector	Number of small & medium-sized enterprises plus individual businesses	+
	Unemployment rate	Ratio of unemployed persons in the labor force	+
Adaptive capacity (Ac)	Economic power	Gross Domestic Production (GDP) per capita	-
	Education level	Ratio of the population with college/university degree or higher	-
	Drainage system	Average length of drainage network per km^2	-
	Vegetation	Ratio of afforestation coverage areas in the city	-

+: the indicator has a positive relationship with vulnerability; -: the indicator has a negative relationship with vulnerability.

Flood risk in a certain region is usually relative, changeable and with multiple components. Studies suggest that although a flood disaster system's relative risk is closely associated with its components' conditions, the overall flood risk is not the aggregation of its components' probability/vulnerability (Li et al. 2013). Thus in this paper, we try to demonstrate in detail each of the components of a flood risk rather than simply calculate a quantitative figure to suggest the risk level.

2.4 Method for flood response analysis

It is indeed of paramount importance to discuss current response measures in the PRD cities and the necessary improvements based on the flood risk analysis. Here a novel framework is applied. The major and interrelated responses are classified in relation to four phases of flooding: precaution by risk identification, warning by forecasting, relief through emergency management and post-flood recovery (details in section 5). The framework also shows the pathways or areas to be strengthened in the context of climate change and urbanization in the PRD area.

3 Climate change in the Pearl River Delta

3.1 Observation records of general and extreme climate

A rate of 0.39°C per decade in temperature rise in the PRD has been observed from 1971 to 2011 (Figure 2a); the city centers warmed even more due to urbanization effects (He and Yang 2011). Aside from the general increasing trend, the number of annual hot days (daily maximums temperature is greater than or equal to 35°C) increased as well, based on records from 29 monitoring stations in the PRD area during 1956-2005. After the 1990s the trend rises much more significantly. The urban heat island effect is thought making a certain contribution to this trend (Chen et al. 2011b).

The precipitation trends in the latest five decades show very weak increase in the PRD area (Figure 2b). Aside from this, the inter-annual variability of precipitation is much more notable relative to the trend in variability of precipitation, which means that extreme precipitation events occurred frequently. Further calculation of the annual rainy days during the period 1957-2009 presents a significant decrease rate of 2.79 days/decade. Thus, an increased annual precipitation with a decrease in the number of rainy days means that the rainfall intensity has increased at the PRD area. An example of this is that Huilai County in east Guangdong recorded 603.5mm rainfall within a six-hour period on June 25, 2010, setting a half-century record (Chan et al. 2010).

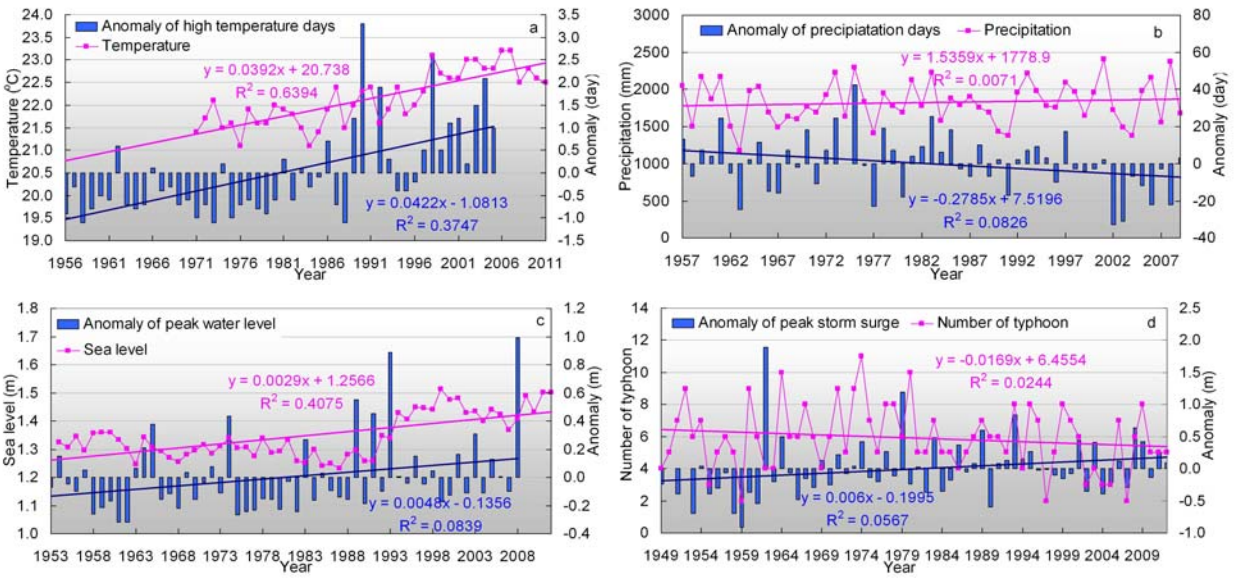

Figure 2. Changes of temperature (a, PRD area), precipitation (b, PRD area), sea level (c, Pearl River estuary) and typhoons (d, Hong Kong) in the last several decades. The value 0 in all anomalies indicates the respective average value (Data sources see the text and refer to section 2.2).

According to the China Sea Level Report 2012, a sea level rise of more than 100mm occurred over the last 30 years at the sea area of east Hainan Province (Pearl River mouth). According to annual data of local tide gauges, the sea level at the Victoria Harbor of Hong Kong experienced a clear rise with an average annual value of 2.8mm between 1954 and 2012 (Figure 2c). As a result of sea level rise, together with a narrowed and silted riverbed, the measured maximum water level of the Pearl River estuary has increased gradually over the past years (Kong et al. 2010). Monitored records of the tide gauges at Denglongshan and Hengmen show a trend of rising peak water levels (1953-2008) and extreme values in 1993 and 2008, as shown in figure 2c.

The PRD is the main landfall area of tropical cyclones and typhoons from the Northwest Pacific and the South China Sea. The annual number of tropical cyclones landed in this area was found to be slightly decreasing (Figure 2d), recorded by HKO. However, the landing areas are more concentrated and the strength of landed typhoons is increasing (Yang et al. 2009). The associated peak storm surge was also increasing in the last 60 years (Figure 2d). Although it is difficult to explain exactly the relationship between global warming and tropical cyclones, it is likely that peak wind speed and rainfall in tropical cyclones will increase if the climate continues to warm (Lei et al. 2009).

3.2 Climate change based on reanalysis and modeling

Results of reanalysis and simulation draw several trends of temperature and precipitation change regarding different scenarios (Figure 3). During the past period 1948-2005, there was a decrease in temperature in the first half and an increase in the second half, while for the whole period temperature changed comparatively little (Figure 3a). The trends of temperature change in three RCP scenarios all indicate an increasing tendency, but with a difference of more than four degrees till the year 2100. The same work on annual mean precipitation shows an increasing trend in the past but no clear trend in the future three scenarios. However, there are significant fluctuations in annual mean precipitation changes under all the scenarios, reaching around 1500 mm difference. In summary, the temperature increase of this area is expected to continue and precipitation is going to show more extremes with no obvious trend.

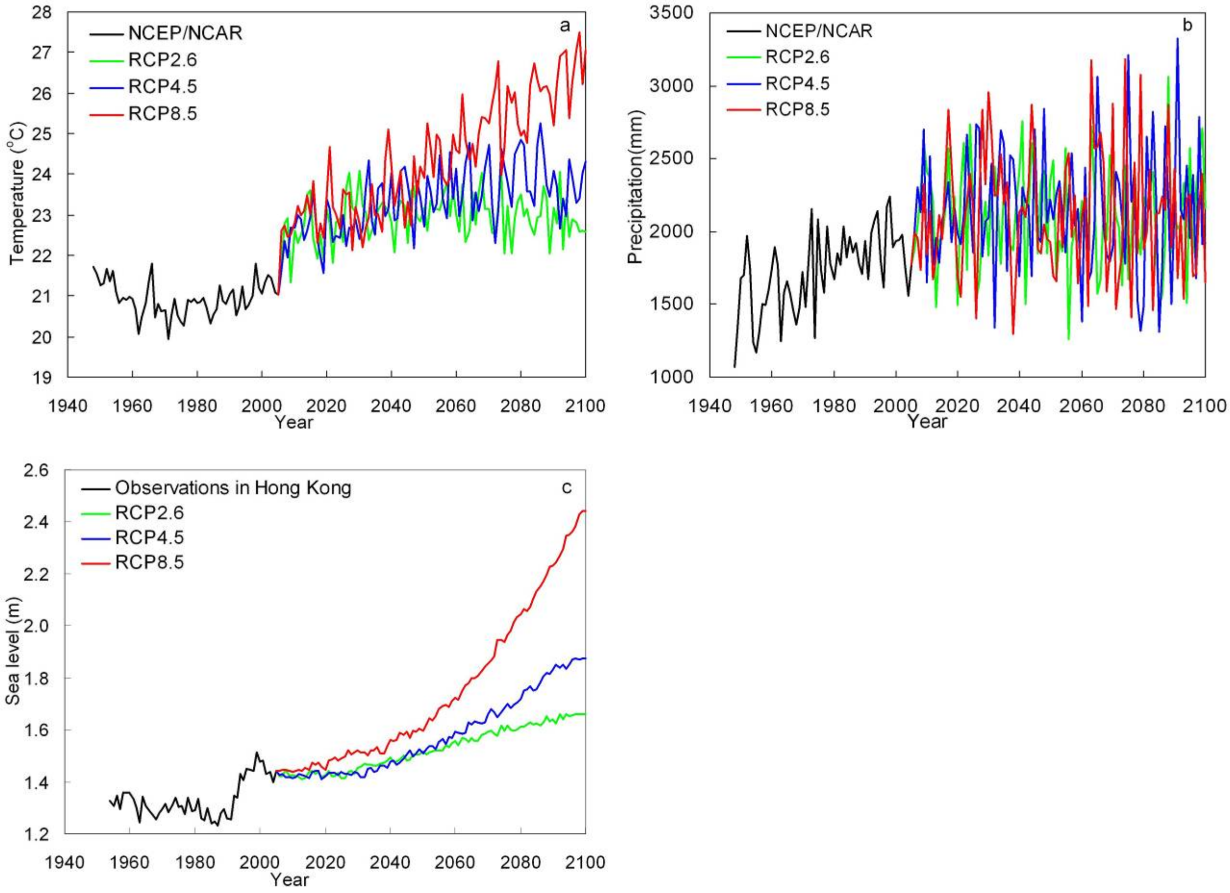

Figure 3. Annual mean temperature (a) and precipitation (b) in Guangdong Province (including PRD) for the period of 1948-2100 and sea level (c) in the Pearl River estuary (Hong Kong) during 1954-2100. The year 2005 divides the past trend under NCEP/NCAR reanalysis (a, b) or observations (c) and the future simulation under RCP8.5, RCP4.5 and RCP2.6.

We trained the sea level projection model (Equation 1) using observed temperature and sea level data in Hong Kong during 1954-2011, resulting in $a=0.0061$, $b=-0.0137$ and $T_0=22.5430$. Then the above emulated temperature data for 2005–2100 in three RCP scenarios (Figure 3a) are used to generate mean sea levels in the same scenarios during the same period. The result (Figure 3c) shows an overall sea level range from 1.66 to 2.44 m for the year 2100 at the Pearl River estuary, which is 22 to 100cm higher than the sea level in 2005.

The MK-test supports further statistical analysis of the modeled climate changes above, showing their trends with 95% confidence level (5% significance level) (Table 2). For the past climate characteristics, there is significant increasing trend in temperature, sea level and their anomalies. No clear trend is seen in precipitation and typhoon numbers. However, there is a decreasing trend in the anomaly of precipitation days and an increasing trend in the anomaly of peak storm surge, which indicates that precipitation intensity was increasing and typhoon-related storm surge severity was also increasing. These trend analysis are good complements to the linear regressions in figure 2. For the future climate projection, the trend tests show no trend in precipitation by all scenarios and in temperature by scenario RCP2.6.

Temperature has an increasing trend within scenarios RCP4.5 and RCP8.5, and sea level goes increasing in all scenarios.

Table 2 Mann-Kendall trend tests with 5% significance level for climate change characteristics in figure 2 and figure 3.

Item*		Kendall's tau	p-value (Two-tailed)	alpha	Trend test Interpretation
Past T	Temperature	0.590	< 0.0001	0.05	Increase
	Anomaly of high temperature days	0.453	< 0.0001	0.05	Increase
Past P	Precipitation	0.041	0.671	0.05	Non-trend
	Anomaly of precipitation days	-0.201	0.036	0.05	Decrease
Past Sl	Sea level	0.324	0.000	0.05	Increase
	Anomaly of peak water level	0.188	0.042	0.05	Increase
Past Tp	Number of typhoon	-0.100	0.274	0.05	Non-trend
	Anomaly of peak storm surge	0.220	0.011	0.05	Increase
Future T	RCP2.6	0.103	0.138	0.05	Non-trend
	RCP4.5	0.439	< 0.0001	0.05	Increase
	RCP8.5	0.704	< 0.0001	0.05	Increase
Future P	RCP2.6	0.006	0.937	0.05	Non-trend
	RCP4.5	-0.006	0.937	0.05	Non-trend
	RCP8.5	-0.007	0.917	0.05	Non-trend
Future Sl	RCP2.6	0.899	< 0.0001	0.05	Increase
	RCP4.5	0.899	< 0.0001	0.05	Increase
	RCP8.5	0.963	< 0.0001	0.05	Increase

* T: temperature; P: precipitation; Sl: sea level; Tp: typhoon.

3.3 Findings integrated with literature results

Table 3 gives a generalized overview of historical trends in the recent past and likely future trends under continued warming conditions for the PRD and the surrounding areas. Our own findings based on observation records, reanalysis and modeling are also added at the end of the table for comparative purposes. Due to the use of different computing methods, such as spatial interpolation and statistical averaging, these studies show slightly different results. Overall, an increased trend of temperature, precipitation and sea level at PRD was seen in the past and is expected in the future.

Table 3. Literature overview of recent and likely future trends of climate change in Pearl River Delta, China

Source	Region	Recent trend			Future trend		
		T	P	Sl	T	P	Sl
Yu et al. (2007)	Guangdong	↑	0	↑	↑	↑	↑
Tang et al. (2008); Huang and Zhang (1999)	Macau	-↑	-↑	↑-	-↑	-↑	↑-
Zhang et al. (2009a); Fischer et al. (2011); Chen (2012); He and Yang (2011)	PRD	-↑↑-	00-↑	----	----	----	----
Li (2011); SOA China (2011); Shi et al. (2008); Huang et al. (2004)	PRD	----	----	↑↑↑↑	----	----	↑↑↑↑
Du and Li (2008); Li et al. (2012)	South China	-↑	-↑	--	↑↑	↑↑	--
Wang et al. (2011)	East River	-	-	-	-	↓	-
Hong Kong Observatory (2012); Ginn et al.	Hong Kong	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑

(2010)							
Li (2009)	PRD	↑	0	-	↑	↑	-
Own analysis using observation records	PRD	↑	0	↑	-	-	-
Own analysis using reanalysis and modeling	PRD	0	↑	↑	↑	0	↑

T: Temperature; P: Precipitation; Sl: Sea level.

↑: increase; ↓: decrease; 0: no significant change; -: no result in mentioned source literature. Combinations of the symbols indicate results in different sources, e.g. -↑ means the 1st reference doesn't give result on the item and the 2nd reference gives a result of increase.

Industrialization and urbanization are continuing in the PRD area and are generating greater emissions of greenhouse gases which represent a large latent source of future warming and additional changes (He and Yang 2011). The changes would include a great increase of warm days and nights in this area. Yu et al. (2007) indicates a temperature increase of 2.8°C by 2100 in Guangdong and the strongest warming would very likely occur in the highly developed PRD area. The city scale temperature projection in Macau claimed an increase of about 2.7°C by the end the 21st century with a significant reduction of cold days (Tang et al. 2008). Integrating these results with the above simulated temperature trend under the midrange mitigation emission scenario RCP4.5, the temperature in the PRD area is likely to increase 2.5-3°C by the end of the 21st century.

In the future, the specific rates of precipitation change may vary but the trends are mostly increasing, except from an abnormal decrease in the East River basin (Wang et al. 2011). However, the general trend does not necessarily mean a wetter PRD due to more frequent occurrences of extreme weather. For instance, the frequency of extreme rainfall would increase with significant seasonal differences and the increasing precipitation will be composed mainly of rainstorms/heavy rain. Therefore, overall precipitation of the PRD area will probably increase slightly in the later years of this century (Du and Li 2008; Ginn et al. 2010), but temporary and local precipitation will be highly variable.

The magnitude of mean sea level rise in the PRD area has been predicted as 20 cm to 25 cm (Ren 1993), 22cm to 33 cm (Huang et al. 2000) and 13cm to 17cm (Chen et al. 2008) between 1990 and 2030, or 40 cm to 60 cm between 1990 and 2050 (CAS 1993). A recent review on this issue claimed a less than 20cm sea level rise by the year 2030, compared with 2010 (Li 2011). For better integration and comparability, we calculate the annual rate of these predicted mean sea level rises and it indicates a range from 0.33cm to 1cm per year. Even the lower limit of these predicted rates is higher than those of the previously analyzed historical records.

3.4 Uncertainties

Uncertainties in climate change research derive mainly from the nature system, the model/analysis process and the data used (Allen et al. 2000; IPCC 2007b; Hawkins and Sutton 2009; Schilling et al. 2012). Uncertainty is a feature of many climate components and is thus unavoidable. For example, a rainfall event may be predictable, but the intensity, duration, location and their combinations are somehow stochastic phenomena. This automatically produces uncertainties for the future projections.

Uncertainty in model process reflects the incomplete knowledge of the system or limit capacity of available hardware (e.g. computing capacity). In this study, the adopted MPI-ESM-LR model works well in global scale while its accurancy in regional level is with uncertainty. The semi-empirical approach (equation 1) has a basis that there is a robust link between surface temperature and sea level, however, the connection of the two exists for sure but is not so clear and depends on the choice of input data (Rahmstorf et al. 2012). We still take this approach because we are only interested in the change in the mean sea-level, not its interannual variability. The random variations around the mean projection would add a few centimeters uncertainty, but this effect is less and less significant as in the case for projections to the year 2100.

Further, different sources, criteria and time-series of data will give uncertain results. We used the observatory data in about last 50 years to analyze the climate characteristics of the PRD. However, the time series is relatively short and the results may be different if a longer time duration is used. The same case is the location choice of data source. For instance, data from other tide gauges at the PRD area would show slightly different sea level characteristics due to variant local conditions.

4 Flood implication and risk in the PRD

Understanding the risk of climate-related flooding in specific regions and communities is a challenging task. For the PRD, we try to clarify it from three dimensions suggested by Apel et al. (2008): flood hazards, vulnerability and uncertainty.

4.1 Flood hazard and its probability in the PRD

4.1.1 Rainstorm and river flood

The stream flow variations show close relations with precipitation changes in Pearl River basins, implying tremendous influences of climate change on hydrological processes (Zhang et al. 2009b). In figure 4, large flood impacts (economic loss and population flooded) coincide clearly with high precipitation in most of the years, while low precipitation means fewer flood impacts in 2004 and 2011. However, floods are not only related to total precipitation, but also to extreme rainfall. In 2003, the total precipitation is relatively low, but flooded populations reach quite high numbers because the strong typhoon Dujuan hit PRD directly with extreme rainfall and strong winds. This is also the case for typhoons. What usually matters more is the intensity rather than the typhoon frequency, as three typhoons (Bilis, Kaemi and Prapiroon) swept the area successively in 20 days between July 14 and August 3, 2006, causing extremely high damages. As previously stated, annual precipitation, extreme rainstorms and typhoons in the PRD area are all projected to rise over this century, thus the probability of flood occurrence is expected to increase accordingly.

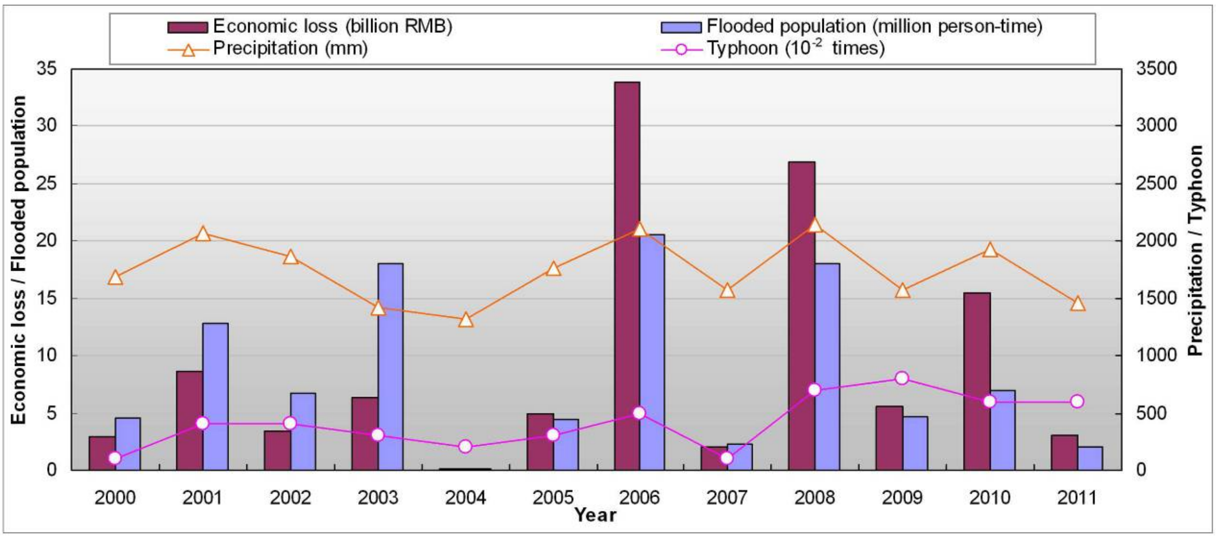

Figure 4. Annual precipitation, typhoon and flood impacts in Guangdong Province between 2000 and 2011. Economic loss and flooded population indicate impacts mainly caused by water flooding, but also include those by tropical cyclones, typhoons and the associated influences. The special unit "person-time" indicates a combination of flooded people and flooded times. The real number of typhoon occurrences is multiplied by a factor 100 for better visualization in this figure. (Own representation based on the Water Resources Bulletin of Guangdong Province from 2000 to 2011).

Flooding in cities is usually called waterlogging, which occurs frequently in PRD cities like Hong Kong and Shenzhen. The highest ever recorded hourly rainfall at the Hong Kong Observatory is 145.5 mm on 7 June 2008, which caused 672 local waterlogging events (HKO 2012). Accordingly, in Shenzhen 16 of the 18 flood events recorded during 1980-2000 were caused by rainstorms (Yuan et al. 2003). In addition, large areas of land are covered by buildings and cements due to urbanization, which increase the surface runoff and rainwater accumulation for waterlogging. In the context of expected extreme precipitation and continuing urbanization, waterlogging is increasingly possible for city centers due to fast rainwater accumulation and in old city areas due to poor local drainage. Although continuing construction of drainage projects enables the PRD cities to get rid of waterlogging, it cannot be entirely eliminated as extreme rainstorms may happen or drainage channels may be blocked.

While the eastern areas of the PRD face a lot of local small-scale floods caused by intensive rainfall, the western and northern parts suffer more river flooding, usually caused by large-scale precipitation. A sharp increase in precipitation would require further water storage capacity for flood control along the river, while unexpected precipitation reduction would affect the impoundment. Given that the frequency and intensity of extreme weather have shown significant change, tremendous influence on hydrological processes could be expected and further flood risks in the river basin scale are implied. Indeed, the decrease in flood frequency and increase in flood-affected population or assets in the last decades have been noticed in the Pearl River basin by Chen et al. (2012).

4.1.2 Sea level rise and flood implications

In the case of the previously predicted 0.33-1cm sea level rise per year, large areas would be heavily and severely affected in this century. At the same time, the return period of a certain high water level will be shortened, increasing the possibility of suffering tidal inundation. Adding to this is the fact that a large number of existing tidal flood defenses are below the standard set by the provincial government (Chen and Chen 2002), increasing the flood probability to the local population. If the PRD region fails to take precautions, it will suffer multiple serious impacts of inundation, storm surges, dike failure and drainage difficulties.

Sea water inundation. Using calculations based on the elevation data of ASTER GDEM (V1), the PRD land areas with elevation below or equal to sea level is 541.03 km^2 which accounts for 0.97% of the whole PRD plain. Below 1m the area is 1185.03km^2 (2.12%) and below 3m it is 4390.19km^2 (7.86%). Therefore, even the modest projected sea-level rise of 13cm by 2030 (Chen et al. 2008) will result in inundation that affects more than 500 km^2 in the PRD area and a large part of the delta plain will be vulnerable to tidal inundation if no preventative measures are taken. If the sea level rises 1m, more than 1000 km^2 of the PRD land will be lower than the sea level with cities like Zhuhai, Zhongshan, Dongguan, Guanghzhou and Foshan being affected seriously. Considering the overlap of dense population (You et al. 2013) and low areas (flood prone areas, Yang et al. 2010), the potential impact of sea water inundation is considerable. While the question how many areas and population will be affected would highly depend on the distribution and standards of the flood protection projects.

Storm surge. Even areas with elevation above 1m will also suffer notable risks from storm surge. Records between 1991 and 2005 show that the range of maximum sea level rise caused by storm surges in the Pearl River estuary was between 1.9 and 2.6m (Zhang 2009). In a severe typhoon, such as Typhoon Wanda of 1962, storm surges could be 4m higher than usual (Lee et al. 2010), enough to cause coastal flooding. This indicates that the projected increase of typhoon intensity would aggravate the destruction of storm surges and cause the coastal area to flood more easily.

Dike system failure. One obvious impact of rising seal level is that coastal dikes and other coastal structures will lose effectiveness. Undoubtedly, sea level rise will result in increased opportunities for sea water to overtop the coastal tides. As shown in Huang et al. (2000), the dikes originally designed for 100-year flood prevention in PRD could not even resist a 20-year flood in the case of a 30cm sea level rise. The coastal dike system would also be damaged by more salty tides which erode dikes although they are not seen as floods. Sea level rise would push saltwater to intrude further into inland rivers and erode inland flood-fighting facilities as well, which poses a serious threat to river bank security.

Drainage difficulties. In the case of sea level rise, backwater flow at the river estuary will decrease the river drainage capacity and intensity and prolong the drainage duration. Actually, about 1% of the PRD land is currently below sea level and many low areas rely on electromechanical drainage. It is clear that the number will increase along with sea level rise and more lands will suffer increased flood probability and longer waterlogging.

4.1.3 Emerging flood hazards from human-induced factors

The climate-related impacts are not the only causes for flood hazards in the PRD area. Since 1980, the coastline of PRD has undergone extraordinary changes due to urbanization and economic development. Such developments also increase the likelihood of flooding due to human-induced hydrological changes, which include:

- Rapid urban development results in intensive development in the rural areas including the flood-plains. Research revealed that urban growth contributed 8.1mm increases of annual runoff depth during the decade 1989-1997 in the PRD (Weng 2001). In Foshan, approximately 60% of the newly built-up land was converted from pond, farmland, forest and shrub during 1988-2003, and further forest and shrub were changed to farmland to compensate the farmland loss (Zhang et al. 2008). This shift of natural ground to human-controlled land has altered the rainfall-runoff relationship, which leads to increased and earlier flood peak flow, shorter flood duration and increased flood volume.

- In order to meet the water demand of an increasingly dense population, excessive exploitation of groundwater in the PRD has led to land subsidence, making the delta more vulnerable to flooding (Huang et al. 2004).
- Rapid urbanization drives significant riverbed dredging for construction materials. Although river dredging could potentially increase the channel cross-section and reduce the flood risk, intensive dredging and abnormal riverbed excavation exacerbates river bank erosion and therefore increases the probability of riverbank outburst (Luo et al. 2007).
- The growing population occupies an increasing river beach by land reclamation along the Pearl River estuary, which seriously narrows the river channel and reduces the river's natural capacity for draining and regulating flood water. Flood threats will very likely increase in this situation if no remedial action is taken. Moreover, natural flood water storage has been sacrificed, as seen in the drainage of large natural wetlands for urban development around the Shekou Peninsula in Shenzhen.

4.2 Vulnerability assessment of PRD cities

Apart from flood frequency, societies worry about flood risk due to their vulnerability (Balica et al. 2012). This section analyses the vulnerability of PRD cities to flood hazards by identifying exposure, sensitivity and adaptive capacity. Then the findings are combined with a quantification assessment to describe the relative vulnerabilities.

4.2.1 Elements of vulnerability

Flood exposure is defined as the predisposition of a system to be disrupted by a flooding event due to its location in the same area of influence (Balica et al. 2012). As adopted in the PRD urban area, flood exposure indicates the degree of predisposition of urban sections to suffer from flood hazards. In fact, nearly all the areas of the PRD are exposed to different types of floods. Regions in the upper and middle PRD are exposed to fluvial floods due to the high density of a criss-crossing river network, while the coastal region is seriously exposed to floods from typhoons, storm surges, salty tides and sea level rise (Yang et al. 2010). Furthermore, high precipitation indicates a high potential of pluvial flood in a certain area. The urbanization that follows rapid economic and population growth can increase flood risk and expose many more people to flood hazards. In addition, urban development has been a very prevalent and strong trend, with expansion into a lower and flatter coastal zone, which exacerbates exposure to both river flood and sea level rise.

The IPCC (2007a) argued that sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The system can be anything that are valuable in the urban society, but people and assets are the two key components. Flood sensitivity is first expressed in terms of the situation of the disadvantaged people in PRD cities. Most of the seasonal migrant workers (famers who go to cities for temporary jobs), laid-off workers and other low-income people (fishermen and women, self-employed etc.) are in the weakest positions. Experiences have shown that they are the groups that are most sensitive to hazards, most easily harmed and most difficult to recover (Shan 2011). Rapid changes in the cities required a lot of public infrastructures, as well as private properties, which together significantly increase sensitivities of certain sub-regions. Furthermore, small & medium-sized enterprises plus individual businesses are also sensitive to flood impacts as they are mostly unaware of and unprotected from disasters. Severe flooding in the PRD area will lead to recession of the industry and trade in the delta, even affecting the whole country and the world, as the PRD is one of the main manufacturing and trade centers in China. The interdependence of people, infrastructure and economy give the PRD cities a high sensitivity to flood hazards.

The flood prevention system has been improved significantly in the last thirty years in all the PRD cities, which includes series of reservoirs, dams, dikes, detention basins and drainage networks managed both on a basin scale (e.g. Office of Flood Control and Drought Relief) and municipal scale (e.g. Command Center for Flood, Drought & Typhoon). However, uneven adaptive capacities exist in many aspects. Firstly, compared with advanced hardware facilities, there is still shortage of public awareness and knowledge of flood prevention. In particular, vulnerable people are often described as "flustered before, helpless in and dependent after disaster" (Qu et al. 2009). Secondly, local communities, unlike the city government, are loose and inefficient organizations. They lack not only money but also necessary resources, information and facilities. A high proportion of immigrants due to large-scale industry development further causes heterogeneity and psychological disagreements within the community (Rosemary and Jennifer 2003), resulting in reduced social interaction and a weak network. Therefore, it is difficult to practice self-rescue and mutual help in these communities in case of a flood disaster. Last but not least, obvious differences exist among PRD cities regarding the economic strength and level of development. These differences may negatively affect cooperation in flood prevention, e.g. challenging the balance of rights and obligations or stressing different topics and attentions.

4.2.2 Quantification of integrated vulnerability

This section quantifies and combines the three elements (E, S, Ac) of vulnerability into one flood vulnerability index (Figure 5), based on the methodology in section 2.3 and the indicator system in table 1. Of all the eleven cities examined, Hong Kong is the most exposed city to flood hazards due to the high precipitation, high urbanization and steep terrain, causing extreme river flow. Including Hong Kong, Macao, Shenzhen and Guangzhou, the central cities are generally exposed more than the others as low lands (less than 3m above sea level) are highly developed with intensive human activities and properties. Zhongshan also shows a high exposure because of its large area of low lands and intensive river-nets. Zhaoqing is the least exposed city out of eleven, because it has relatively fewer assets to expose and it suffers little from the sea.

Macao leads the sensitivity ranking, followed by Hong Kong and Shenzhen, which indicates that high-density population and production are particularly sensitive to impacts and disadvantaged sections (e.g. old people, unemployed labor, small business) should be the core concern in addressing flood threats. Zhaoqing and Huizhou, as less developed cities in the PRD area, are also highly sensitive to floods. This is the case mostly because both have a large proportion of sensitive population (less than 15 and older than 65 years old) which is a result of young labor migrating to central cities. Hong Kong and Macau have almost equally high adaptive capacity to flood, mostly because both have obviously more soft flood control measures than the other cities, such as better education, information availability, economic power and advanced infrastructures. When combining the exposure, sensitivity and adaptive capacity, the flood vulnerability index ranks Zhongshan, Dongguan and Macao as the top three most vulnerable cities in this area, while Hong Kong, Shenzhen and Guangzhou rank in the middle. Therefore, even though the exposure and sensitivity indicators are still significant in the most developed cities, flood vulnerability and potential risks can be mitigated greatly by improving flood-control measures (adaptive capacity).

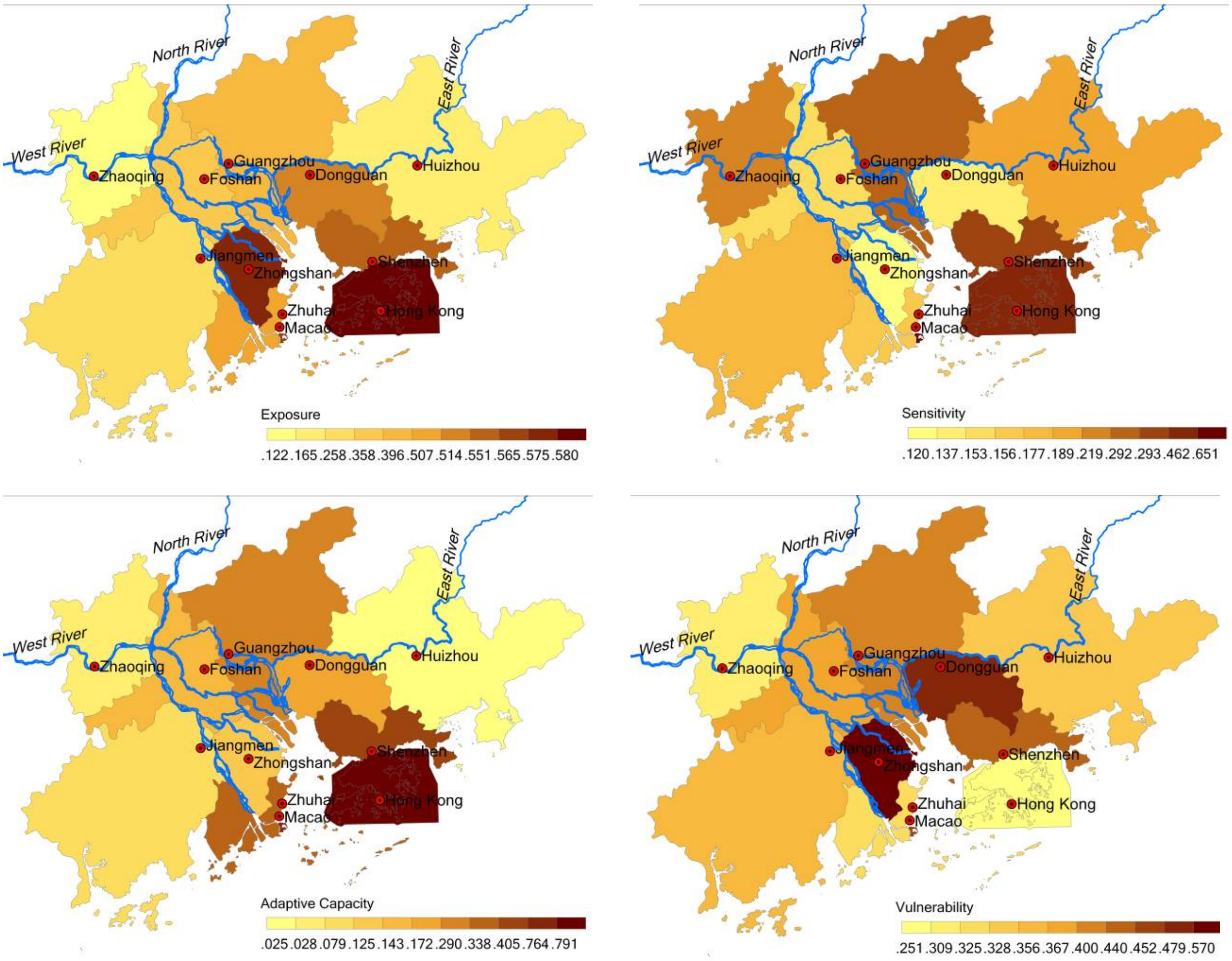

Figure 5. Relative assessment of the flood vulnerability of PRD cities. The factor's value of a city is relative to that of the others, based on the indicators for exposure, sensitivity, adaptive capacity and overall vulnerability given in section 2.3 and table 1. Higher value of a factor means the relative higher E/S/Ac/V.

4.3 Flood risk and uncertainty

The IPCC special report expresses disaster risk as the combination of physical hazards and the vulnerability of exposed elements (IPCC 2012). Accordingly, flood risks in urban area could be understood as a combination of the probability of occurrence of a flood and the vulnerability of the urban system. As a river delta, the PRD has frequently suffered from flooding in the past. Urban settlements in the PRD are typically located and developed along shorelines and the river estuary, putting them at particularly high risk from flooding and an expansion of the water's edge.

A changing global climate is causing rising sea levels and more extreme rainfall events thus would increase the probability of flood occurrence with high variability. Flood vulnerability of the PRD cities is seen as high, based on the evaluation given above. The two parts together indicate a reliable increase of flood risk in the PRD cities, in particular vulnerable cities such as Zhongshang and Dongguan. As a whole, the PRD areas has more frequently more severe flood risks in the future because it is highly impacted by the combination of urbanization effects and climate-related changes.

However, there are many uncertainties in the flood formation process, which relate to the combined effects of human behaviors at all aspects of the process and specific regional characteristics among cities. Floods in every region, basin, and watershed will be affected differently, depending on the specific precipitation and hydrologic conditions in that area. In addition, land use change together with rapid urbanization plays a role in the change of extreme weather. Urbanization may reduce precipitation by changing surface properties (Kaufmann et al. 2007; Rosenfeld 2000), or may promote precipitation by increasing condensation nucleus, enhancing evaporation and vapor circulation (urban heat island effect) (Jauregui and Romales 1996; Xu. et al. 2010). Thus, the impact of urban expansion on precipitation is complicated, and it may exacerbate local extreme weather events by changing the local atmospheric conditions. In recent years more attention has been devoted to enhancing regional climate change information especially for the highly urbanized PRD (Li et al. 2009; Lin et al. 2009; Zhan et al. 2011).

Although the indicator system gives results of the vulnerability level, it depends highly on the indicators chosen and the data used. Different sources, criteria and time-series of data will give variant results. Especially when the eleven cities are compared in one indicator system, uncertainty rises from input data due to different statistical criteria of these cities.

5 Flood response measures and the way forward

This section is going to discuss current response measures in the PRD cities and the necessary improvements based on the flood risk analysis. The major but interrelated responses are classified in relation to four phases of flooding (Figure 6). The figure also shows the pathways or areas to be strengthened in the context of climate change and urbanization in the PRD area.

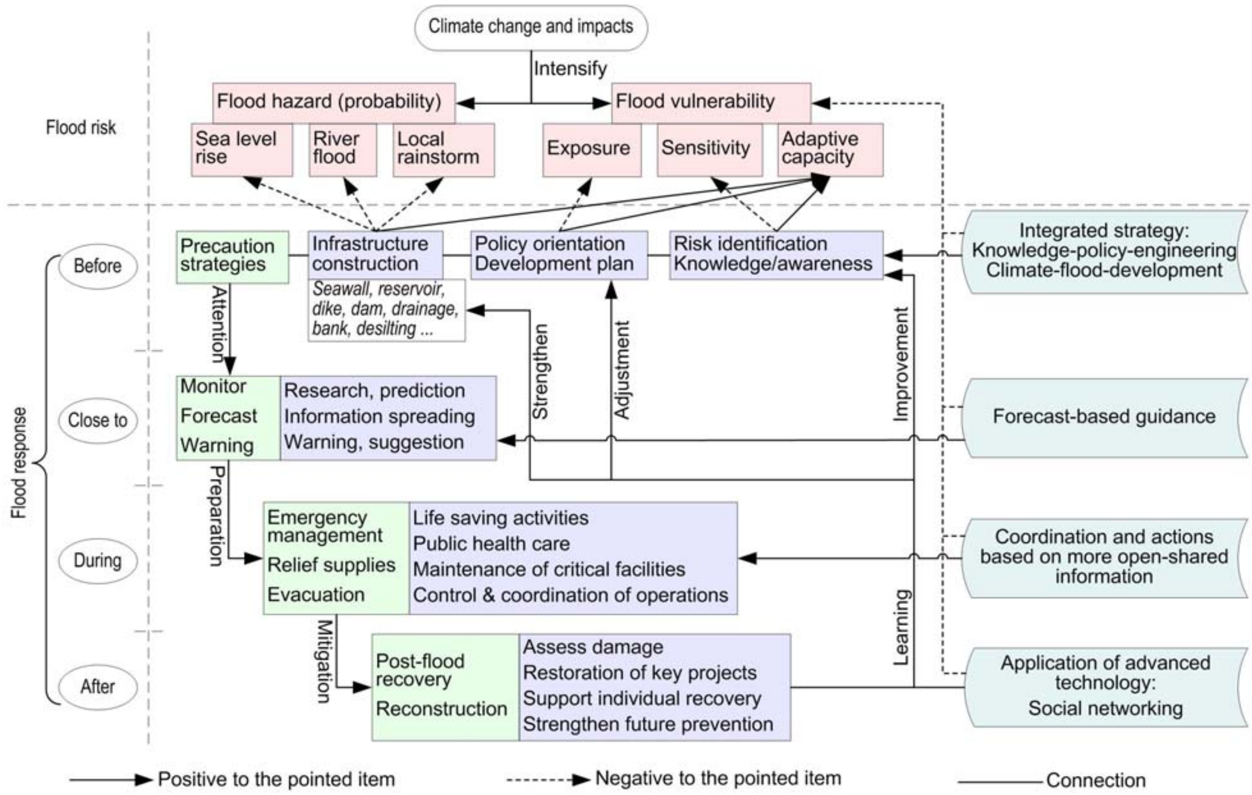

Figure 6 Framework for flood responses in cities of the Pearl River Delta.

5.1 System of flood responses in the PRD

For the emerging flood risks, the best response is precaution (Kreibich et al. 2011), which is sorted in three aspects: risk identification, policy orientation and infrastructure construction. With a fast social-economic development, systematic flood-related engineering was built in the PRD cities and many are in the 12th five-year-plan (2011-2015) of these cities, showing their desires and economic capacity to support it. However, local specifications for the flood-control engineering are not updated despite the increasing flood intensity and magnitude in the context of climate change. In fact, identification and awareness of the flood risk are a prerequisite for engineering and construction. Forward-looking policy guidance and development planning can mitigate the risks as well (Runhaar et al. 2012). However, more urgent necessities for PRD cities are institutional mechanisms for local risk reduction, disaster preparation and self-reliance rather than engineering measures. Considering the generally growing flood risk, the required response capacity must be integrated into long-term development planning and systematic flood control engineering.

Despite the great progress made in the latest decades, forecasting of extreme weather events is still a general problem in the PRD cities. A forecast made 6-12 hours in advance can only reach an accuracy rate of 60% to 70% taking the accurate duration, location and intensity into account (Government Portal of China 2012). Further steps must be made towards improving the forecasting accuracy and the spatial and temporal refinement. In addition, the channels for releasing meteorological information are not well established in most of the PRD cities, and the frequency of meteorological information update is low. These factors make it less possible to spread meteorological information to the recipients in time, while most information quickly becomes useless. Furthermore, specific suggestions should be added together with the warning information as some people don’t understand what the warning signals mean and what activities they should take.

In addition to long-term engineering measures, effective emergency management can save lives in the case of an emergency. Early relief is crucially important but difficult to execute in time because floods often throw the flooded areas into a state of confusion. As the PRD is a dense urban agglomeration, floods often affect several cities at the same time and need to be coped with by the cities together, but collaboration has not been common in practice. There are often challenges in sharing of responsibilities among the cities, like for many other transboundary river management systems (Ganoulis 2006). Despite jurisdictional and administrative separation, sea and river systems must be treated as integrated entities if an optimum flood plan is to evolve. In local communities, better transparency has been called for to ensure the absorption of feedbacks from stakeholders, which would improve the bottom up response framework. Generally, rescuers, materials and technical support are adequate in the PRD cities. But the local people lacks initiative and flexibility in case of emergency rescue because they may not know what measures are available and practical. Thus appropriate emergency response practices are essential at community level.

Recovery depends normally on the remaining local resilience capacity and availability of external rescue resources. First and quick restoration of “life projects” and “product projects” are the key principle for post flood recovery (Zou et al. 2002), which support the basic daily life and business. While overall measures are unable to take care of each individual situation, self-resilience capacity must be strengthened before, during and after a flood. These support activities are expected to increase awareness of the overall flood situation and recovery plan. To compensate huge flood losses, it is not enough to rely on government aids and social donations. Flood insurance is an internationally applied mechanism, while its function is not fully utilized in PRD cities and is therefore worth further consideration. Post flood recovery should include a shift to another type of resilience that includes learning from past events and adapting to future risk. Therefore, recovery work should be carried out excellently as it concerns long-term benefits for the whole area.

5.2 Further improvements for flood response

Flood risks can be reduced by appropriate responding strategies and actions, although specific plans have yet to be executed. Beyond the traditional and basic flood management strategies mentioned above, four more specific measures are suggested to improve the flood response system:

- To develop an integrated "climate response" strategy that unifies the climate change impacts, flood risks and urban developments. In practice, low impact development (van Roon 2007) or Green Infrastructure (Gill et al. 2007) will be the options to support the strategy.
- To implement potent close-to-flood activities based on close-to-flood forecasting and warning. Forecasting and early warning cannot play a role without practical actions. So a definitive guide of actions must be issued, depending on dangers, one day or several hours before the disaster occurs. The options could be to close workplaces and schools, to close low-lying roads or transfer people and assets out of high-risk areas.
- To enhance response capacity of grassroots organizations by information transparency and sharing. Increasing the transparency/availability of knowledge and information to vulnerable populations is crucial so that they can take certain actions in advance. With

available information, public participation could also be integrated into the decision-making process and ensure that disaster management and emergency plans are effective. Furthermore, as awareness of one's own vulnerability to flooding and insights into the effectiveness of coping strategies are driven by direct flooding experiences (Zaalberg and Midden 2010), simulation research by means of interactive models (e.g. agent-based modeling) can support direct flooding experiences on impacts and responses, thereby giving a better understanding of flood impacts.

- To make full use of social networking to improve relief. In social networks, people quickly share and update information about flood warning, traffic jams, inundated areas and shelter location. By exchanging individual knowledge both emergency managers and trapped people could benefit. In several of the major social networks in PRD cities, like Tencent QQ, Renren and Sina Weibo, people are networking to respond to crisis in real time, allowing us to understand what is happening at the level of self-organization. By employing social networks, decision makers are able to confirm the efficacy of certain organizations in flood response as well as identify gaps between response strategy and reality.

6 Summary and conclusions

Mitigating and responding to occurring flood risk has been an issue that challenges the PRD region for years. Additional threats posed by current climate change to the city and its people will likely enlarge the risk scale and the difficulties in addressing it. This paper integrates climate change trends and its potential impacts on flood conditions, flood risk assessment and response measures in the PRD metropolitan area.

The study suggests that by 2100 the temperature will likely rise 2.5-3°C and precipitation increases slightly in the PRD area, while sea level is likely to rise with an annual rate of 0.33cm to 1cm in the near future. The inter-annual variability of precipitation is much more notable relative to its trend variability, which means that extreme precipitation events occur frequently. Flood implications of these trends are pronounced in most of the cities in PRD, although uncertainty remains. The frequency and intensity of extreme weather and climate events have been increasing significantly, together with continuing development in flood-prone areas and natural riverbed siltation, strengthening both the scale and degree of urban flood risk. Although centimeter scale sea level rise may not put the PRD under water, it will however, substantially increase storm flood risk and increase the costs of rebuilding after these storms.

The evaluation of flood vulnerabilities in the PRD cities indicates a complicated situation. Low lying locations with great human welfare and vital infrastructure contribute to the high exposure of these cities, in particular of central cities like Hong Kong, Shenzhen and Guangzhou. These cities also lead the sensitivity ranking, which indicates that vulnerable sections of society (e.g. old people, unemployed labor, small business) are the core concern in addressing flood threats. Fortunately, even though the exposure and sensitivity indicators are significant in the most developed cities, flood risks and potential damages can be mitigated greatly by improving both hard and soft flood-control measures. While the prediction of regional climate futures and vulnerabilities remains inherently uncertain, it is worth further exploration and accurate assessment. With such challenges lying ahead, responding to climate change and managing flood risks can be more sophisticated and needs new knowledge. Decision-makers must proceed with planning and action on the basis of currently available information and estimates.

There are many options available for responding to flood pressures and risks added by climate change. Continuing and strengthening existing measures is a basic requirement for the near future, and aggressive public awareness on climate change impacts and response strategies is required. More work needs to be done to improve the standard of buildings and other infrastructure, so that the cities would be able to cope with the uncertainties of abrupt climate change or extremely high precipitation. Further responding measures, for instance, development of an integrated climate response strategy, release of early warning and action guidance, openness of flood related information to the public and application of the advantages of social networks, are perhaps necessary to improve the current status. Last but not least, studies on the complexity of urban responses to flood risks and climate change impacts must be strengthened, to continue to explore further possibilities.

Acknowledgements

This work was supported by the China Scholarship Council (CSC) and the Cluster of Excellence “CliSAP” (EXC177), University of Hamburg, funded through the German Science Foundation (DFG). We would like to thank Prof. Dr. Hui Lin, Prof. Dr. Yongqing David Chen, Ms. Chunxiao Zhang and Mr. Ming Luo for their support during the fieldwork activities and in this research. We are grateful to Ms. Sarah Nash for improving the language.

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