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Part I

Water-Related Risks under Climate Change

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Pluvial, Fluvial and Coastal Flood Risks and Sustainable Flood Management in the Pearl River Delta under Climate Change

JIANFENG LI, XIAOGANG SHI, YONGQIN DAVID CHEN
AND YANGCHEN LAI

1.1 Introduction

The Pearl River Delta (PRD) is a megalopolis located in South China, which includes the Special Administrative Regions (SAR) of Hong Kong and Macau, and nine cities, namely Guangzhou, Shenzhen, Foshan, Zhuhai, Dongguan, Huizhou, Jiangmen, Zhaoqing and Zhongshan. As the largest city region in the world in terms of size and population, the PRD nurtures about 4 per cent of the Chinese population, i.e. 57.15 million, and produces about 20 per cent of national GDP. The Pearl River Basin (PRB) is the second largest basin in China in terms of annual discharge and provides abundant water resources for the socioeconomic development of the PRD cities (Figure 1.1). Around 80 per cent of the water supply for Hong Kong is from the PRB. The PRB is dominated by a sub-tropical and humid monsoon climate, with over 70 per cent of rainfall concentrated in the summer months, making the PRD region highly exposed to both fluvial floods resulting from high upstream river flow and pluvial floods due to localized heavy rainstorms and inadequate drainage capacities. Due to its coastal location by the South China Sea, the PRD is often attacked by typhoons and thus under the threat of coastal floods, such as the severe inundation of low-lying areas in the PRD due to the storm surge and heavy rainfall caused by super typhoon Mangkhut in September 2018. In this connection, multi-flood prevention and mitigation systems are particularly important for the long-term economic prosperity and sustainable development of this region. Furthermore, along with the merging of individual cities, the recent urban expansion has contributed to an increase in the PRD area by ten-times. The PRD has become one of the world's largest megalopolises in size, population and economic output, causing unprecedented stresses on urban

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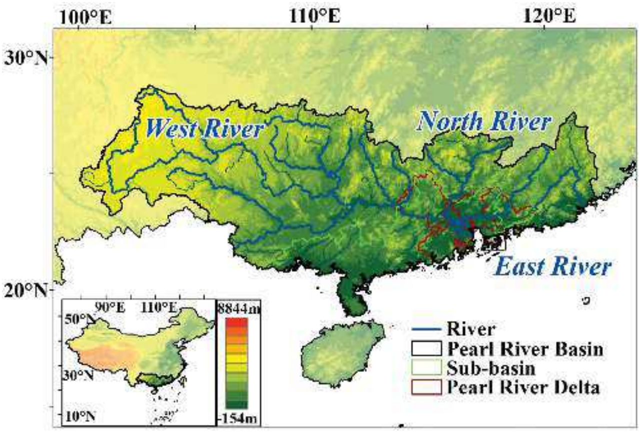

Figure 1.1 Locations of the Pearl River Delta and Pearl River Basin

drainage. Such urban sprawl has substantially altered land–atmosphere interactions in favour of extreme localized rainstorms, as well as increased land surface imperviousness and, thus, enhanced runoff generation, resulting in increases in the risk of both pluvial and fluvial floods.

Due to its unique geographical location and rapid urbanization, the PRD megacity region is affected by various types of floods triggered by different mechanisms, including pluvial, fluvial and coastal floods. Heavy rainstorms caused by various weather systems (e.g., typhoons and convections) usually bring about excessive rainwater inside the cities in a short time. In the PRD, the highly and rapidly urbanized land surface undermines the water storage capacity of the land surface and reduces the capacity of drainage systems due to clogging for various reasons (e.g., trash blockage and back water effect), causing greater threats of pluvial floods. The PRD is located in the estuary of the PRB, which is the convergence of the three major rivers, namely Xijiang (West River), Beijiang (North River) and Dongjiang (East River). Large-scale rainstorms in the upstream of the PRB would cause excessive discharge to the downstream and may trigger fluvial flood hazards in the PRD. In past decades, fluvial floods were the major flood type in the PRD before flood prevention infrastructures such as dikes and dams were built and commissioned. In recent years, fluvial floods have been effectively controlled and prevented, while pluvial floods have become more frequent due to the rapid urbanization; hence, more studies are focused on pluvial floods (Yin et al., 2014; Huang et al., 2018). As the PRD is located on the coasts of the South China Sea, the sea level rises under global climate change and storm surge induced by typhoons are the major causes of coastal floods in the regions (Yu et al., 2018; Hong Kong Observatory, 2019b). Different types of floods may co-occur simultaneously or in sequence because they can be physically caused by the same weather systems. For example, super typhoons can bring excessive rainwater, high storm surge and strong winds and, therefore, lead to pluvial and coastal floods. The co-occurrence of different types of floods have greater impacts on the cities (Ikeuchi et al., 2017; Shen et al., 2019). For instance, coastal floods reduce the city drainage capacity, which makes it more difficult to drain out the flooding water in a city directly resulting from pluvial or fluvial floods.

Under climate change, coastal regions across the world have experienced intensifications of different types of flood hazards. For example, coastal Bangladesh is a delta region affected by multi-type floods such as pluvial, fluvial and coastal floods (Adnan et al., 2019). Among these flood types, pluvial floods are more frequent, while fluvio-tidal floods and coastal floods cause larger inundation areas. Adnan et al. (2019) found that polders in Bangladesh prevent moderate storm surges and fluvio-tidal floods on one hand, but exacerbate the inundation areas of pluvial floods on the other hand. In the Mekong River delta of Vietnam, flood levels depend on the combined effects of upstream flows, sea level rise, storm surges and siltation of the Mekong Estuary. Affected by engineering structures along the Mekong River in Vietnam and nearby countries, the water is deeper in the rivers and channels in these areas because of the increases of flow velocity, bank erosion and siltation, resulting in more frequent floods in the non-protected areas and greater risks of dike failure in the protected areas (Le et al., 2007). The Rhine-Meuse delta in the Netherlands, a well-developed and densely populated delta region in Europe, is threatened by sea level rise and storm surges (De Moel et al., 2011). The long-term efforts in protecting vulnerable areas against rising sea levels, such as mechanic pumping stations and dike-rings, successfully protect the flood-prone areas against floods with pre-defined return periods ranging from 1,250 to 10,000 years in this region. However, combining the effects of population growth, economic development and climate change, the flood damage in the Netherlands is projected to increase ten-fold by 2100 compared to 2000. Thus, flood management in a context of increasing flood risks under climate change is a major challenge for coastal cities across the globe (Vis et al., 2003; Klijn et al., 2012). Therefore, investigating the causes, changes and mitigation measures of multi-type floods in the PRD under climate change carries scientific and practical importance for improving the understanding of climate change impact on flood risks and for formulating mitigation strategies against the increasing multi-type flood risks in a coastal metropolis.

1.2 Localized Precipitation Extremes and Pluvial Flood Risks in the PRD under Climate Change: Observations and Projections

1.2.1 Past Observations and Analyses

Pluvial floods, also called urban waterlogging, are caused by localized precipitation extremes and inadequate drainage capacities of an urban area. The

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PRD is controlled by the sub-tropical monsoon systems, with annual precipitation ranging from 1,000 to 2,000 mm, and the summer precipitation accounts for 72–88 per cent of the annual total, with June being the month with the highest precipitation (J. Li et al., 2017). Over the years, the PRD has often suffered from the impacts of heavy rainstorms. Such extreme rainstorms have led to serious waterlogging and resulted in economic damage and even loss of life in the PRD cities. On 29 May 1889, the centurial extreme rainstorm led to a total rainfall of 697.1 mm in 24 hours, which was about one third of the annual total precipitation, resulting in serious floods and landslides in Hong Kong (Lee et al., 2016). As one of the most destructive rainstorms in the history of Hong Kong, this extreme event ruined a number of roads, killed 27 people and resulted in 17 people missing. The estimated cost of the damage to government property was $112,783 at that time, which was about 6 per cent of the annual government expenditure in 1889. On 7 May 2010, extreme rainstorms caused serious water-logging in Guangzhou, leading to inundated streets and transport chaos (Huang et al., 2018). On 7 May 2017, an extreme rainstorm with a return period of 60 years hit the PRD (Zhang et al., 2019). The rain gauge in Zengcheng district in Guangzhou recorded 586 mm precipitation in three hours, causing severe pluvial floods in Zengcheng, Huadu and Huangpu districts.

Precipitation extremes are the major trigger of pluvial floods. Under global climate change, local changes in precipitation extremes can significantly alter the pluvial flood risks in the affected region. Observations showed that the precipitation regimes in the PRD have changed over the past decades (Zhang et al., 2012). Ai and Wu (2018) indicated that the intensity of rainstorms and the contribution of heavy rainstorms to annual precipitation slightly increased in Guangzhou over 1961–2015. Lenderink et al. (2011) analysed the hourly precipitation observations since 1885 in Hong Kong and suggested that the increases in daily precipitation extremes under global climate change generally follow the Clausius-Clapeyron relation (C-C relation). The C-C relation indicates that the maximum moisture content of the atmosphere is expected to increase with about 7 per cent per degree Celsius when temperature increases. They also found that the hourly precipitation extremes in Hong Kong increased by 10–14 per cent per degree Celsius temperature rise, which is faster than the C-C increase rate and called the super-CC relation. The findings of Lenderink et al. (2011) suggested more intensification of hourly and daily precipitation extremes under global climate change, implying greater risks of pluvial floods.

A number of precipitation indices, which represent various characteristics of precipitation regimes, have been applied to analyse the changes in precipitation in the PRD. Although these indices may differ in the PRD, they generally showed that precipitation had become more intense in the past decades. Based on daily

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precipitation of 1960–2005 from 42 stations across the PRB, Zhang et al. (2012) evaluated the spatial–temporal changes of different precipitation extreme indices, including annual total precipitation amount, annual total rainy days, annual precipitation intensity and annual mean rainy days. The modified Mann–Kendall trend test method was used to detect the trends of these extreme indices. The results showed that the PRB was characterized by increasing precipitation intensity, especially in the middle and eastern parts of the basin where the PRD is located. Frequencies of short-duration wet periods and total precipitation amount have increased in the past decades, raising the risks of floods. Heavy precipitation was associated with wet spells of shorter durations, which suggests that the precipitation process intensified in the PRB, especially in the PRD located in the lower part of the basin. Zhao et al. (2014) analysed the daily precipitation during 1960–2012 and evaluated the changes in another set of precipitation extreme indices across the PRB. They did not find significant trends in the number of heavy precipitation days, however, the simple daily intensity index increased significantly at the 95 per cent level. Other extreme precipitation indices, such as maximum 1-day precipitation, maximum 5-day precipitation and intensity of extreme precipitation with intensity greater than its 99th percentile exhibited no significant trends. They also concluded that Pacific Decadal Oscillation (PDO) and Southern Oscillation Index (SOI) are important factors that affect precipitation changes. Fischer et al. (2012) indicated that extreme precipitation indices in the PRB changed abruptly in 1986 and 1997. Based on the precipitation observations in Hong Kong since 1885, Wong et al. (2011) examined the past trends in precipitation extremes using extreme indices developed by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) under the World Meteorological Organization (WMO). They found that the frequency of 1-, 2- and 3-hour precipitation extremes increased significantly. The contribution of precipitation extremes greater than the daily 95th percentile to annual total precipitation increased substantially by 22 mm per decade. The return period of 1-hour precipitation greater than 100 mm decreased significantly from 37 years in 1900 to 18 years in 2000.

Previous studies mostly focused on the changes in the probabilistic behaviour of precipitation extremes. In recent years, increasing concerns have been drawn to the joint behaviours of precipitation extremes. Zhang et al. (2013) investigated spatiotemporal patterns of historical precipitation extremes in China during 1960–2005 based on Copula, an important tool in the bivariate analysis of precipitation extremes. The joint probability analysis of precipitation extremes showed that precipitation extremes were intensifying in South China, specifically the PRB. The intensification of precipitation extremes in the PRB was associated with the decreasing number of rainy days and increasing number of consecutive non-rainy days, suggesting potential increases in the occurrences of floods and droughts.

1.2.2 Future Projections

Under the future global climate change, the frequency and intensity of extreme precipitation in the PRD are expected to continue to change. Because the spatial resolutions of Global Climate Models (GCMs), a major tool for climate projections, are too coarse for projecting precipitation changes in the PRD at the regional scale, the outputs of GCMs were downscaled to a finer resolution in previous studies. The future projections of the Hong Kong Observatory (HKO), based on statistical downscaling, showed that extremely wet years (i.e., annual precipitation greater than 3,168 mm) would reach 12 years, and extremely dry years (i.e. annual precipitation less than 1,289 mm) would be only 2 years in Hong Kong under the future high-emission Representative Concentration Pathways 8.5 scenario (RCP8.5; Hong Kong Observatory, 2014). The annual number of rainy days was projected to decrease from 102 days in 1986–2005 to 97 days in 2091–2100, and in the same two periods the average precipitation intensity should increase from 23.4 mm/day to 26.7 mm/day as rainy days decrease (Hong Kong Observatory, 2014). The annual number of extreme rainy days were projected to increase to 5.1 days in 2091–2100 from 4.2 days in 1986–2005, and the annual maximum daily precipitation should increase considerably from 221 mm in 1986–2005 to 273 mm in 2091–2100 in Hong Kong (Hong Kong Observatory, 2014). More detailed changes in different precipitation extreme indices in Hong Kong can be found in Figure 1.2. Decreases in the number of rainy days under climate change have been widely reported in different regions, such as the PRB, China, and Europe (Qian et al., 2007; Zolina et al., 2010; Zhang et al., 2012; Li et al., 2013). This can be explained by the increases in maximum moisture content of the atmosphere given temperature rises according to the C-C relation (J. Wu et al., 2015). Given a stable level of water vapour content, it is harder for a warmer atmosphere to reach dew-point temperature.

Li et al. (2013) applied a statistical downscaling method on the basis of Quantile–Quantile relationship and transfer functions to downscale precipitation extremes from the GCM outputs of the Coupled Model Intercomparison Project Phase 5 (CMIP5) to the site scale. The Taylor diagrams showed that the normalized standard deviations of most models are close to 1 and the correlations between the simulations and observations are close to 0.8 or larger, indicating that the downscaled extreme indices were reasonably matched with the observations. The projections based on the downscaled indices indicated that precipitation processes are expected to intensify with increased frequency and intensity in the PRD in the future. Future changes in precipitation extremes exhibited larger

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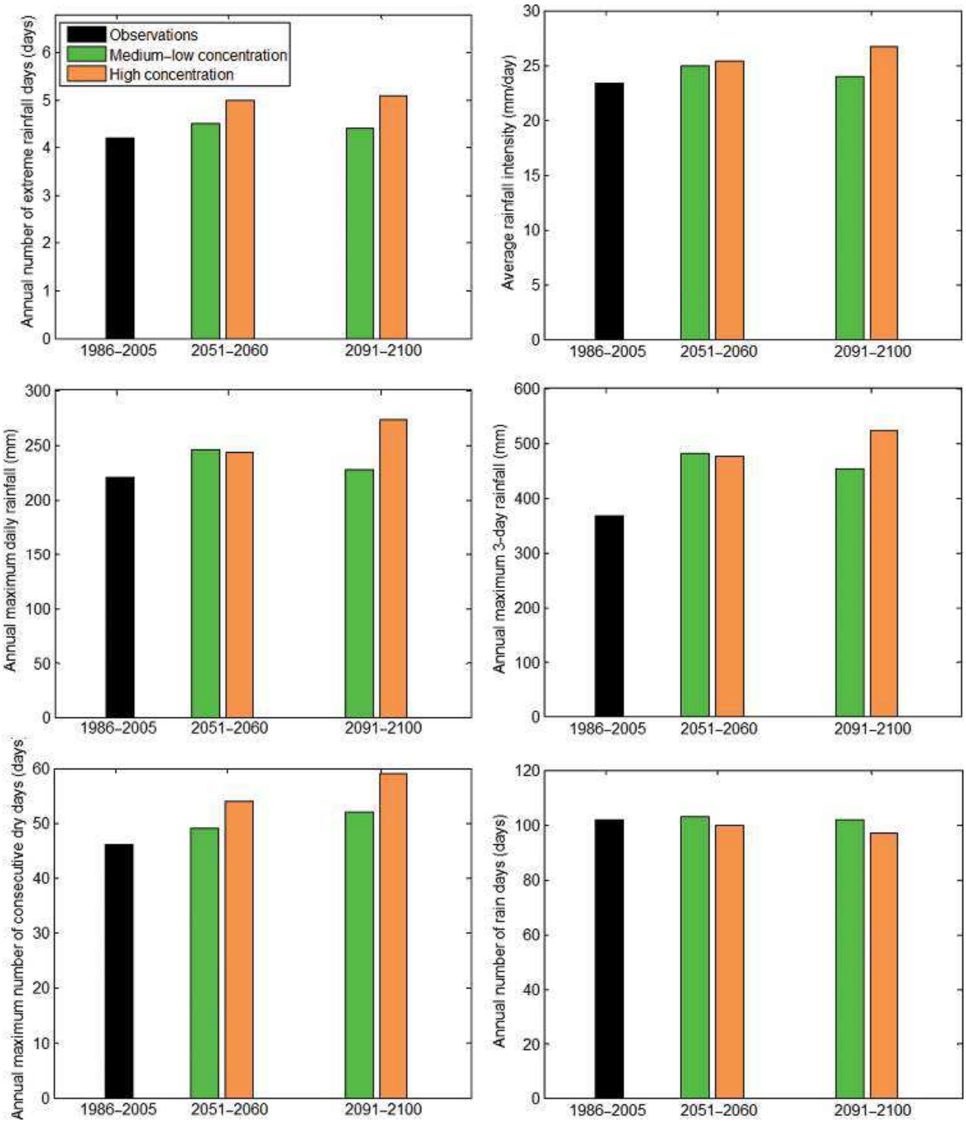

Figure 1.2 Annual number of extreme rainfall days (days), average rainfall intensity (mm/day), annual maximum daily rainfall (mm), annual maximum 3-day rainfall (mm), annual maximum number of consecutive dry days (days) and annual number of rain days (days) in 1986–2005, 2051–2060 and 2091–2100. Black denotes the actual value of the extreme index. Green and orange denote low–medium concentration and high concentration scenarios, respectively (adapted from climate projections of the Hong Kong Observatory, 2014)

magnitudes of change under RCP8.5 than RCP2.6. The future changes in precipitation extremes are gradual processes (Figure 1.3). The change rates of precipitation extremes are expected to be higher in the eastern part of the PRB and lower in the western part during 2010–2039 under RCP2.6 and RCP8.5. In

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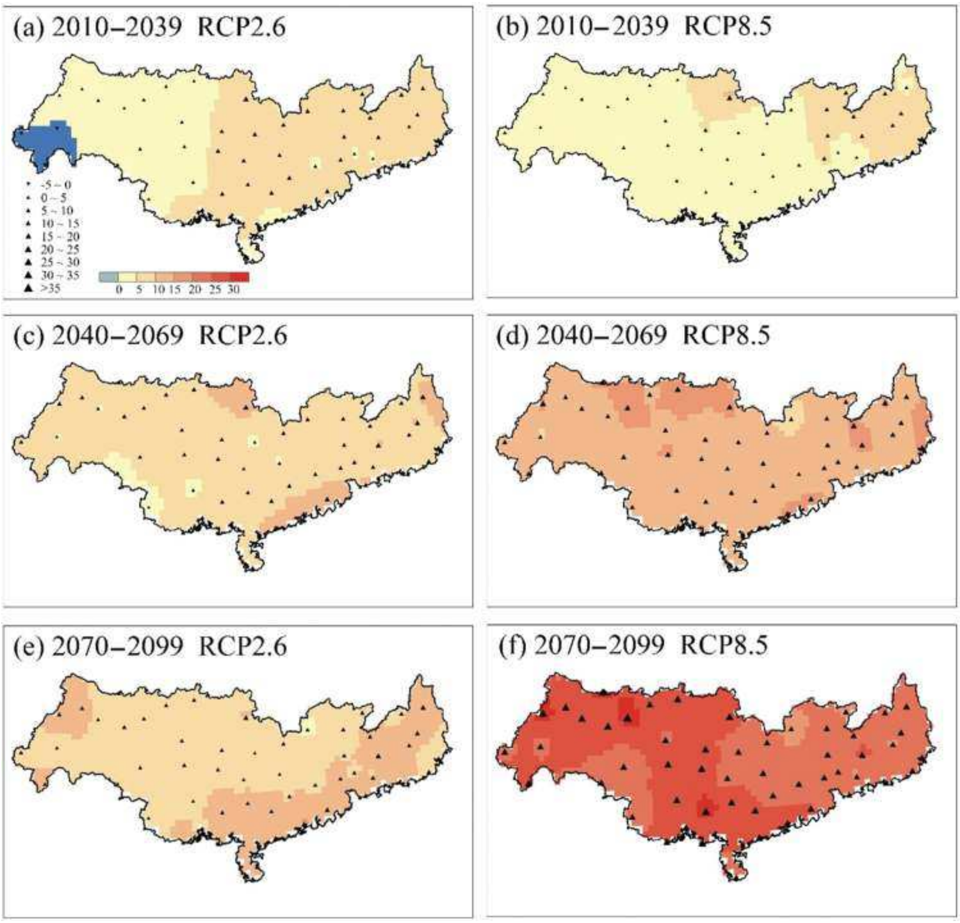

Figure 1.3 The changes (%) in maximum 5-day precipitation amount of (a) 2010–2039, (c) 2040–2069 and (e) 2070–2099 under RCP2.6, as well as of (b) 2010–2039, (d) 2040–2069 and (f) 2070–2099 under RCP8.5, compared to 1960–2005. The upward triangle denotes the index of that station increases and the downward triangle denotes the index of that station decreases (adapted from Li et al., 2013)

2040–2069, the change rates are projected to be similar across the PRB. During 2070–2099, the change rates are projected to be higher in the southern and eastern parts of the PRB under RCP2.6 and the central and northwestern parts under RCP8.5. The directions of changes may alter during the temporal evolution of precipitation extremes. Changes under RCP8.5 become more pronounced over time. Under the peak-and-decline RCP2.6, changes of some indices are not expected to decrease correspondingly during 2070–2099, even though the radiative forcing predicted during 2070–2099 is less than that during 2040–2069. The