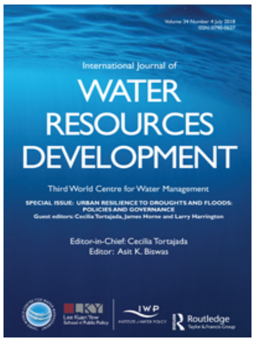

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The impact of weather extremes on urban resilience to hydro-climate hazards: a Singapore case study

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ABSTRACT
Changing frequencies and intensities of extreme weather events directly affect settlement vulnerability; when combined with rapid urbanization, these factors also influence urban resilience to climate-related hazards. This article documents how urban resilience can generally be maximized, before examining how it is impacted by extreme hydro-climatic events (i.e. droughts and floods), with a specific case examination for Singapore. In particular, analysis of Singapore's climate from 1950 to 2015 indicates (1) a warmer environment, and (2) recent periods of more intense surface dryness. Lastly, this article suggests how specific climate information regarding extreme event attribution can aid municipal stakeholders involved in urban resilience policy.

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Introduction

Urbanization – where people move from dispersed, mostly agrarian or 'rural' settlements to densely populated towns with more complex 'urban' socio-economic activities – has been rapidly increasing worldwide since 1945. As of 2007, more than half of the world's population now live in cities of varying sizes, and the rate of this rural-to-urban transition shows little sign of abating (United Nations, 2015). Geographically, most urban growth over the next 15 years will be concentrated in developing nations in Asia and Africa (Table 1). This prodigious demographic expansion includes cities in South-East Asia, a region which (1) saw its 'urban' population grow from 26 million to 294 million between 1950 to 2014, (2) includes a completely urbanized city-state (Singapore), and (3) will see the capital cities of the Philippines (Metro Manila) and Indonesia (Jakarta) rank amongst the 25 largest cities by 2030.

Consequently, urbanization directly and indirectly influences various aspects of the Earth system, and much Anthropocene-themed research examines its specific impacts on climate systems across all scales (e.g. Grimm et al., 2008). These impacts include the micro- and local-scale modification of temperatures that are well documented through research on the ubiquitous urban heat island phenomenon (e.g. Yow, 2007; for Singapore, see review by

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Table 1. Estimated 2015 and projected 2030 urban population of the world's largest cities.

	2015		2030	
Rank	City	Population (millions)	City	Population (millions)
1	**Tokyo**	**38.0**	**Tokyo**	**37.2**
2	**Delhi**	**25.7**	**Delhi**	**36.1**
3	**Shanghai**	**23.7**	**Shanghai**	**30.8**
4	São Paulo	21.1	**Mumbai**	**27.8**
5	**Mumbai**	**21.0**	**Beijing**	**27.7**
6	Mexico City	21.0	**Dhaka**	**27.4**
7	**Beijing**	**20.4**	**Karachi**	**24.8**
8	**Osaka**	**20.2**	**Cairo**	**24.5**
9	**Cairo**	**18.8**	**Lagos**	**24.2**
10	New York	18.6	Mexico City	23.9
11	**Dhaka**	**17.6**	São Paulo	23.4
12	**Karachi**	**16.6**	**Kinshasa**	**20.0**
13	Buenos Aires	15.2	**Osaka**	**20.0**
14	**Kolkata**	**14.9**	New York	19.9
15	Istanbul	14.2	**Kolkata**	**19.1**
16	**Chongqing**	**13.3**	**Guangzhou**	**17.6**
17	**Lagos**	**13.1**	**Chongqing**	**17.4**
18	**Manila**	**12.9**	Buenos Aires	17.0
19	Rio de Janeiro	12.9	**Manila**	**16.8**
20	**Guangzhou**	**12.5**	Istanbul	16.7
21	Los Angeles	12.3	**Bangalore**	**14.8**
22	Moscow	12.2	**Tianjin**	**14.7**
23	**Kinshasa**	**11.6**	Rio de Janeiro	14.2
24	**Tianjin**	**11.2**	**Chennai**	**13.9**
25	Paris	10.8	**Jakarta**	**13.8**

Note: Asian and African cities are in bold font.
Source: United Nations, 2015.

Roth & Chow, 2012); regional-scale variations in hydro-climates such as urban-induced precipitation changes (Shepherd, Carter, Manyin, & Burian, 2010), and global-scale climate change (e.g. disruption to climate due to land use and land cover change, and greenhouse gas emissions). For global climate disruption, the central physical characteristic is the non-stationary, slow variation of averages (i.e. means of temperature and precipitation) compared to pre-industrial baselines (e.g. Intergovernmental Panel on Climate Change [IPCC], 2013). While adaptation to these slow changes may be possible by society at large, the greatest impact and risk to urban areas will occur for changes in frequency of extreme weather and climate events (Wigley, 2009), such as heat waves, droughts, floods and severe storms.

Against this background of unequivocal physical impacts arising from climate-driven hazards, there are substantial differences in urban governance structures and policies to minimize physical exposure – and correspondingly lower risk and improve adaptation – to these climate hazards. The confluence of these physical and policy aspects in urban areas leads to complications in how geophysical hazards affect municipal settings. In dealing with hydro-climatic hazards, such as a lack of surface or subsurface water (i.e. drought) or a surfeit of precipitation (i.e. flooding arising from extreme storms or intense or prolonged precipitation events), municipal authorities and policy-makers should maximize the existing *resilience* of urban areas. How these cities react to climate hazards depends on several geographical factors, including (1) the location of cities relative to coastal and low-elevation regions that may be more exposed to changes in hydro-climate, (2) high concentrations of people with differing income levels and access to resources and usage of urban infrastructure, and (3) increasing systemic complexities in policy implementation depending on heterogeneous local governance structures across coupled human-natural systems (e.g. Liu et al., 2007).

This article will describe how resilience – especially in urban areas – is defined and can be maximized, before examining how changing climates can directly affect urban resilience through the impact of extreme hydro-climatic events (i.e. droughts and floods). It will document the case study of Singapore, noting how two recent events have affected present and future urban resilience to climate change. Lastly, the article argues that an examination of the attribution of extreme climate events from recent history can illuminate the broader relationship between climate change and urban resilience, an examination which may be useful for municipal stakeholders who will face an uncertain future of more frequent climate extremes.

Urban resilience in the face of climate change

Resilience is a complex term having several definitions depending on disciplinary and geographical contexts, and its use is gaining prominence given the increasing impact of climate change on society (e.g. Leichenko, 2011). A commonly used definition (IPCC, 2012), which will be applied in this article, is

> the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.

In the context of climate change adaptation, Buurman and Babovic (2016) also discuss and highlight the importance of system *flexibility* from engineering and design perspectives when dealing with uncertainty. Leong (2016) also notes two contested concepts of resilience within these definitions: first, resilience as *persistence* in the face of hazards through recovery, with a bias towards preserving a system's status quo; second, resilience as not just 'bouncing back' from a setback but continuous stakeholder *adaptation* to impacts of environmental fluctuations. Given the non-stationarity of environments during the Anthropocene (e.g. Castree, 2015), greater focus on the second, more responsive, concept may be more relevant when discussing urban resilience to climate hazards. A distinctive characteristic of urban resilience is having municipal policies that alter or adapt existing urban system *processes*, with no predetermined aim of altering the system to a desired state. There is thus a nuanced difference vis-à-vis sustainability, in which the attention is to desired *outcomes* – and the implicit normative decisions – that is a key motivation for stakeholders who explicitly seek urban system transformations (Redman, 2014).

In 'urban' and 'rural' areas, a major difference occurs between how resilience processes to hazards are driven. In the former, economic capital (e.g. financial resources) is the primary driving force, whereas community capital (e.g. place attachment and extent of preparedness and emergency response skills) is critical for developing disaster resilience in rural areas (e.g. Cutter, Ash, & Emrich, 2016). While access to economic resources is important in building resilience in cities, there are other factors to consider when maximizing urban resilience to hazards. Ahren (2011) suggests five strategies for urban planners and stakeholders to consider; these are useful tenets to apply in cities with changing environmental conditions:

- Expanding the *multi-functionality* of spaces. This can be done through strategic planning of settlement features having multiple intertwined or combined functions integrated across horizontal or vertical spaces. One example is the comprehensive low-impact development applied in Singapore for sustainable urban stormwater management, which maximizes hydraulic connectivity, flood control and water quality. This integration is done through constructed wetlands, rain gardens, rooftop gardens and canal restoration (Lim & Lu, 2016).

- Spreading hazard risk through *redundancy and modularisation*. This strategy entails structure development and policy planning that avoids 'placing all your eggs in one basket' with a singular or centralized system to protect against hazards. Usually, urban redundancy is a feature that is higher in large cities, such as in the industrialized West, that have more resources and practise decentralized planning (Rumbach, 2016). For instance, a single levee may be effective in protecting a small settlement against channel flooding, but may result in a 'levee effect' of increased building development that multiplies flood risk (Smith, 2004). Increased resilience to extreme flood events can subsequently result through redundant multiple levees, or other alternate upstream flood management systems, as it grows in size.
- Maximizing the *biodiversity and social diversity* of adaptation development measures. This approach increases urban ecosystem service provision offered with appropriate adaptive tools. A relevant example is the use of multi-scale urban green spaces (e.g. street trees and parks) in reducing urban warmth, which is a prevalent feature of most large cities (e.g. Demuzere et al., 2014; Deng, Cardin, Babovic, Santhanakrishnan, & Schmitter, 2013). Apart from the direct impact of reducing heat, indirect impacts on a diverse range of system risks also occur. These include (1) increased infiltration that augments urban flood control, (2) provision of potential refuge spaces for wildlife, and (3) recreational spaces for park visitors.
- Enhancing *multi-scale networks* and *increasing system connectivity*. A single urban element (such as a park or green space) has relatively limited impact on reducing overall system hazard risks. A network of connected parks at larger spatial scales, however, enables increased resilience through connecting drainage channels linking lower-order and higher-order streams to enhance flood control, and also by including a second-order benefit of running or walking trails for park users. These features reduce inefficiencies arising from fragmentation, and can be illustrated in Singapore's island-wide network of green corridors (Tan, 2006).
- *Anticipatory adaptive design and planning* to account for imperfect knowledge. Generally, urban policies reactively apply lessons from past hazards to restoring infrastructure in ways that make these structures slightly safer than before (Olshansky, 2009). A more resilient city goes beyond this concept of 'resilience as persistence', and considers plans and designs of projects and policies aimed at enhancing flexibility in adapting to environmental fluctuations (e.g. de Neufville & Scholtes, 2011; Geltner & de Neufville, 2012; Zhang & Babovic, 2011). These 'experiments' or pilot testbeds allow stakeholders to gain new insights from the results of monitoring and analysis.

Recent research based in Asia indicates low levels of resilience to increasing risks from hydro-climate hazards in numerous cities (Douglass, 2016). In South-East Asia (2015 population of ~600 million), the rapid rate of urbanization is clear, with urban population increasing from 15.5% (in 1950) to 41.8% in 2010 (Yap, 2013). Further, its major cities experiencing rapid growth are located in either coastal or riverine locations subject to greater exposure to hydro-climatic hazards. Thus, changing societal exposure to extreme weather should be discussed.

Challenges to urban resilience posed by extreme weather or climate events

Weather and climate extremes, such as heat waves, cold snaps, heavy precipitation events, droughts, tropical cyclones, and wildfires, appear increasingly common in recent years worldwide (e.g. Herring, Hoerling, Kossin, Peterson, & Stott, 2015). These extremes can be defined as events in which a measured climate property exceeds either upper or lower thresholds compared to what was previously recorded at that location; these thresholds apply to either event frequency or event intensity. These events directly modify urban resilience by (1) directly increasing climate exposure and the resulting vulnerability of urban residents and property to harm and damage (e.g. Chow, Chuang, & Gober, 2012; Cutter & Finch, 2008), while (2) possibly reducing various coping and adaptive capacities largely managed by municipal policies. Depending on whether these extremes are accounted for during urban development and planning, the likely result is that settlement resilience would diminish depending on the frequency or intensity of the weather event.

Statistically, these extremes are indicated by (1) shifts in the mean, (2) increases in variability, and (3) changes in kurtosis or skewness in the probability distribution of climate variables (IPCC, 2012). The probability distribution changes may be minor in magnitude, but result in significant decreases in return period – and corresponding increasing risks of extreme events at a given location (Wigley, 2009). Globally, the physical reasoning that underpins the increased frequency and intensities of extreme events can be explained by radiative energy changes to the Earth System. The climate system is destabilized by an energy imbalance primarily due to increased emissions of human-induced greenhouse gases; all weather events, extreme or not, are affected by climate change because the environment in which they occur is warmer and moister than it used to be (e.g. Held & Soden, 2006; Trenberth, 2012).

However, inherent complexities exist with direct attribution of *individual* extreme events to climate change. The paradox is that information on the causes of smaller-scale individual extreme events has greater policy relevance than those for global-scale attribution, but it is much more challenging to assess, given (1) data paucity (i.e. lack of high-quality long-term data records for temperature, precipitation and other climate variables across the globe) that often precludes frequency analysis for specific locations, and (2) limitations of coupled Earth Systems modelling at the appropriate scales for the event (e.g. issues of downscaling global to regional climate models to ensure accuracy of seasonal monsoonal precipitation over South-East Asia; McSweeney et al., 2015).

Apart from the challenge of direct attribution with respect to global climate change, other complexities are apparent when considering certain extreme weather events at regional – and especially local – spatial scales. For instance, while precipitation extremes and sea-level rise are physical factors that increase the risk of major floods in settlements, other significant factors such as geography (e.g. inland vs. coastal location) and infrastructure (e.g. the extent and effective management of flood control measures) are also critical in determining how climate change influences flood magnitudes and frequencies.

Even with these challenges, stakeholders aiming to maximize urban resilience would prefer up-to-date knowledge about the underlying causes of these events. Currently, there are two approaches to attribution of extremes (Trenberth et al., 2015). The first is mainly descriptive in relating the particular extreme event to associated weather and weather patterns (e.g. 'the drought was caused by El Niño') that, however, do not directly examine how climate change is involved. The second attribution approach assesses the role of human activities, and especially of human-induced climate change, in the extreme event. Usually, this analysis is done via a properly framed hypothesis with an explicit climate change component, e.g. 'For this extreme drought, how was regional evapotranspiration enhanced by climate change, and how did the increase influence the resulting moisture deficits, soil aridity, and wildfire risks?' Two recent reports compiled by the American Meteorological Society (Herring, Hoerling, Peterson, & Stott, 2014; Herring et al., 2015) applied these approaches in assessing 45 extreme events in 2013 and 2014 for possible anthropogenic signals in terms of radiative drivers and land cover changes.

These analyses of past extreme events have some utility for adaptive resilience planning, but further information through robust model projections would arguably be more useful. To that end, the IPCC – in its Special Report on Managing the Risks of Extreme Events (IPCC, 2012) and its Fifth Assessment Report (IPCC, 2013) – evaluated the impacts of both recent and future extreme events for different regions. There are notable variations in observation and confidence (based on analysis of extant evidence) of whether hydro-climate hazards such as droughts and floods could have a large anthropogenic climate change component influencing the magnitude of these extremes (see e.g. Table 3-1 in Intergovernmental Panel on Climate Change, 2012). That said, a potential criticism of this large-scale review is that the information lacks local context and therefore diminishes its applicability for cities and their resilience to these hazards. Results from case studies may yield useful information, and examples from Singapore will be discussed in the next section.

Urban resilience to changing climate extremes: a case study of droughts and floods in Singapore

This article focuses on instances in which hydro-climatic extremes have affected resilience in a highly urbanized South-East Asian city (Singapore: 1°N, 104°E, 2015 population ~5.5 million). In the course of its development from a colonial trading settlement in the nineteenth century to a major metropolis today, the risk to water-related hazards has diminished, largely due to proactive planning in developing its resilience to climate-related shocks, and this section examines how the city-state's direct exposure to severe weather events can influence its resilience to climate change.

Resilience to droughts and floods

The development of Singapore's relatively strong resilience to hazards is well documented in its water management (e.g. Tortajada, Joshi, & Biswas, 2013). Arguably, this is best illustrated by the actions of its national water agency (Public Utilities Board, PUB), which is responsible for water resource and drainage management throughout the island-state. Historically, incidences of water rationing occurred in the 1960s due to lower-than-normal precipitation and a shortage of water supply from the island's catchment areas (*Straits Times*, 1963), and flooding issues arose with heavy monsoonal precipitation coupled with a lack of drainage infrastructure, e.g. the island-wide floods on 10 December 1969 that resulted in five deaths, and with road and rail links to Malaysia cut off (*Straits Times*, 1969). From these early hazardous circumstances, the agency's actions were instrumental in (1) reducing the island's total area of flood-prone land from about 3200 ha in 1970 to less than 34 ha in 2015 (Public Utilities Board, 2015), and (2) ensuring the secure provision of water through diversification of water supply through the policy of Four National Taps: water imports from Malaysia, water from local catchments, desalination from reverse osmosis, and recycled water (Tortajada & Joshi, 2013).

Recently, however, two instances of extreme weather have directly affected Singapore's urban resilience to hydro-climate changes in different ways. First, during a 62-day period from January to March 2014, less than 1 mm of total rainfall was measured at the climatological station of record at Changi Airport. The near-zero precipitation measured during the month of February 2014 was 159 mm below the 1961–90 climate normal. The lack of precipitation during the same period also extended to parts of Peninsular Malaysia, where 350,000 households in Selangor and Johor States had water rationed in urban areas (Agence France-Presse, 2014), and large regions of Thailand, which underwent severe drought in the first four months of 2014 (National News Bureau of Thailand, 2014). Yet, despite the increased hydro-climatic stress from this extreme event across the region in early 2014, mostly business-as-usual water consumption occurred with no restrictions in either domestic or industrial water use. Ziegler et al. (2014) suggested that this event was an opportunity to investigate other means of increasing resilience to drought through the addition of another 'national tap' through offshore groundwater extraction. Despite the dry circumstances, a slight increase in domestic water consumption from 400 to 420 million gallons per day (1.51 to 1.59 billion litres per day) was measured during the drought period (*TODAY*, 2014). The outcome suggests that existing urban resilience (as persistence) was strong in this instance of meteorological drought, but Leong (2016) argues that the increase in national water demand suggests that the conception of resilience (as adaptation to environmental shocks) may be lacking among its water users.

The second instance of extreme weather pertains to the significant and increased frequency of reported flash flood events occurring in the city-state over the past 30 years, most notably with two June 2010 flood events in the popular shopping district of Orchard Road. These floods occurred from a combination of short-duration, very intense rainstorms over the Orchard Road area, and a partially blocked culvert that restricted drainage from the inundated area. While no deaths or injuries were reported, the knee-deep flood waters resulted in S$ 23 million (US$ 17 million) of insurance claims (Chow, Cheong, & Ho, 2016). While the likelihood of urban flash-floods locally is high given the large degree of impermeable surface cover, combined with low elevation, tide levels, and coastal location, significant increases in (1) the measured intensity of rainfall events and (2) the recorded frequency of large rainfall events (over 70 mm/h) in 1980–2010 appear to be a causative factor in this recent prevalence of flash floods (Ministry of the Environment & Water Resources, 2012; Beck et al., 2015). In other words, a trend of more frequent and intense rainfall events in recent years can overwhelm existing drainage infrastructure not designed to anticipate increases in extreme precipitation. Ssince 2013 PUB has embarked on a series of drainage improvement projects to improve the overall urban resilience to extreme-precipitation-driven flash floods. These measures include installation of water detention tanks, additional diversion canals, the widening or deepening of existing canal drainage networks, and the replacement of drain inlets with gratings designed to reduce blockage or choking of inlets from debris (*AsiaOne*, 2013).

Shifting climate conditions in Singapore?

Even with these instances of urban resilience to these two hydro-climate events mentioned in the preceding section, there remains a concern that future extreme weather events associated with climate change could present challenges to physical and social adaptation in the island-state. The ongoing implementation of drainage improvement by PUB since the 2010 flash floods is a perceptive move, especially given that future projections clearly indicate a trend of more intense and frequent rainfall under climate change warming scenarios (Marzin et al., 2015).

A more pressing concern remains, though, for resilience to future droughts. The 2014 meteorological drought event was a clear anomaly, especially compared to the previous drought or 'dry spell' record of 18 days in early 2008. Another oddity was that the event occurred during a non–El Niño period; usually, Singapore and the rest of South-East Asia experiences drier-than-normal conditions during El Niño events (e.g. Li, Meshgi, & Babovic, 2016). However, when examined in a paleo-climatic context for South-East Asia, Cook et al. (2010) showed that the duration of the 2014 drought was not uncommon when the annual Palmer Drought Severity Index (PDSI) was inferred from climate proxies. While present-day attribution of this event provides no link to climate change (McBride et al., 2015), it must be stressed that this study was descriptive in its approach to attribution (i.e. the drought was due to the seasonal contraction of the inter-tropical convergence zone), and did not attempt to use climate modelling to examine larger climate change drivers.

To further investigate the unusualness of local observed climate trends, 1950–2015 data from the WMO meteorological stations of record in Singapore were analyzed for the frequency distribution of annual mean temperature and total precipitation anomalies (the raw monthly climate data and accompanying metadata are given in Table A1 in the online supplemental material, https://doi.org/10.1080/07900627.2017.1335186). The analysis highlights the changing frequencies of the anomalies of annual extremes when compared to the World Meteorological Organization's 1961–90 climate normal for Singapore (e.g. after Hansen, Sato, & Ruedy, 2012). The positive skew of annual temperature anomalies is clearly apparent, with the most extreme extending to greater than three standard deviations (3σ) (Figure 1). The decadal trends of temperature anomalies also indicate a trend of more recent years becoming warmer than normal (Figure 2), with recent years frequently being more than 3σ above long-term normal. Annual precipitation anomalies, however, do not appear to have a similar right- or left-wards shift to more extreme conditions during the period of analysis (Figure 3).

The analysis of annual temperature and precipitation anomalies is helpful in indicating larger-scale potential changes in local climate, but it does not give a complete insight into potential drought conditions; that requires finer-scale data and a consideration of relevant soil moisture conditions. Therefore, monthly PDSI from January 1950 to December 2015 was calculated through the method of Jacobi, Perrone, Duncan, and Hornberger (2013) to examine the island's long-term trend of relative dryness. These data were derived from Table A1, combined with knowledge of the predominant local soil type being the Rengam Series with an available water content value of 350 mm/m (Rahman, 1981). PDSI ranges from −10 to +10, with positive (negative) values indicating periods of surface water abundance (water stress). In certain cases, PDSI may be a limited indicator of drought – the index does not account for seasonal storage of water as snow or ice, and assumes that precipitation is immediately available for storage or evapotranspiration (e.g. Alley, 1984); however, these are not critical at low latitudes, and its use is relevant in this case to indicate periods of surface water stress.

The results indicate that increases in 'severe' or 'extreme' drought conditions (when PDSI is less than −3 or less than −4, respectively) were strongly related with El Niño events in

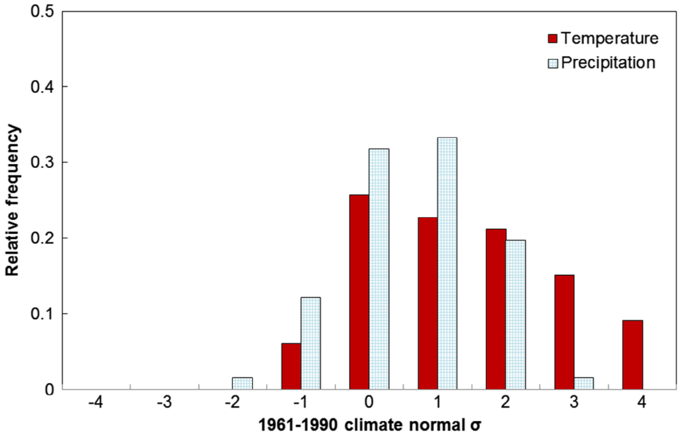

Figure 1. Frequency distributions of annual mean temperature anomalies (in red) and annual total precipitation anomalies (in blue) for the period of 1950–2015 obtained from the Singapore climate data-set in Table A1. Each year's anomalies are compared with the standard deviations (σ) of the 1961–90 climate normal, and are binned accordingly.

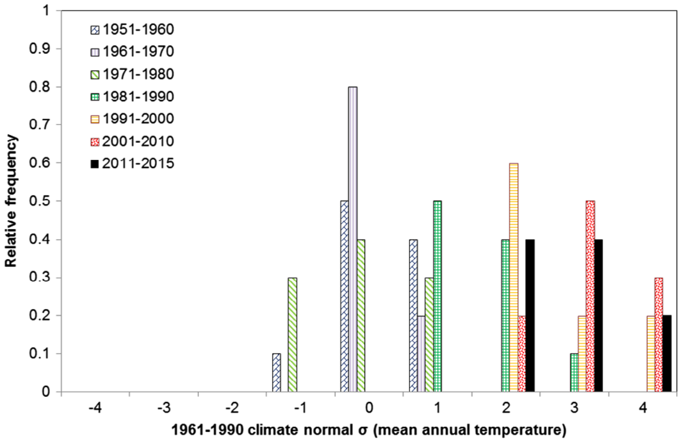

Figure 2. Distribution of 1951–2015 mean annual temperatures anomalies grouped by decadal periods compared with the standard deviations (σ) of the 1961–90 climate normal from the Singapore climate data-set in Table A1. The rightward shift in distribution for more recent data to +3σ is very distinct. NB: The 2011–15 data are five-year averages.

South-East Asia in 1963, 1972, 1982, 1997 and 2015 (Figure 4). Notably, recent drought conditions appear to be increasing in magnitude in conjunction with the increases in mean temperatures measured locally. A slight decreasing trend in monthly PDSI over the study period is present, suggesting a possible shift since 1950 to a climate that increases potential evapotranspiration and produces higher water-stressed conditions. With concerns over potentially more frequent and extreme El Niño events under current emission scenarios (e.g. Cai et al., 2015), future drought conditions need to be included in Singapore's water policy, especially given that water imports from Malaysia will end in 2061.

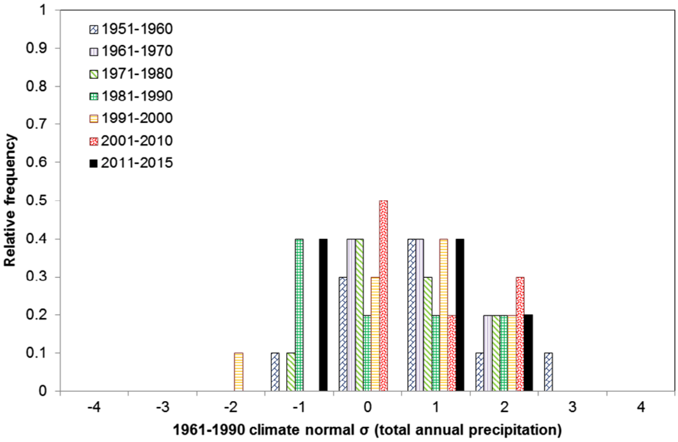

Figure 3. Distribution of 1951–2015 mean annual precipitation anomalies grouped by decadal periods compared with the standard deviations (σ) of the 1961–90 climate normal from the Singapore climate data-set in Table A1. NB: The 2011–2015 data are five-year averages.

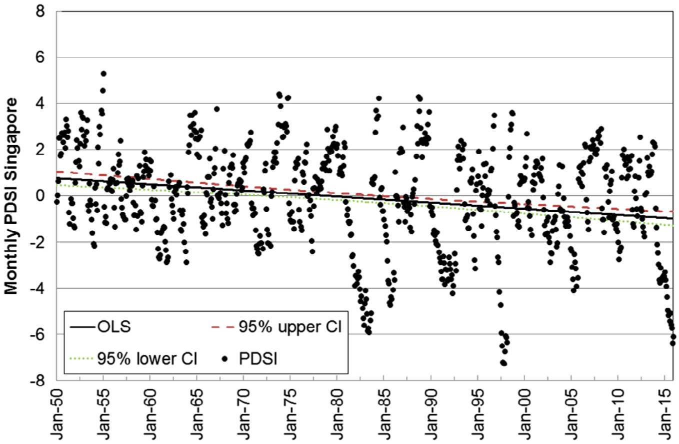

Figure 4. Monthly Palmer Drought Severity Index (PDSI) time series for 1950–2015 and associated OLS trend (with 95% confidence intervals) calculated for Singapore based on (1) data from the Singapore climate data-set in Table A1, (2) Rengam Series soil available water content from Rahman (1981), and (3) derived by the method described by Jacobi et al. (2013).

Conclusion: improvements in climate attribution and application to resilience planning

While the examination of Singapore's resilience makes for an interesting local case study, It should be stressed that the issue of variations in urban resilience to climate change extends to a much larger regional (i.e. Asian) and global context. There is a strong likelihood of more frequent or intense climate extremes being a strong external physical stressor on the resilience of cities. This factor will test existing levels of urban resilience in major cities across a range of potential hydro-climatic hazards, such as for existing infrastructure, e.g. dams, levees and drainage control that may not be able to cope with the impacts arising from precipitation extremes, or for policies implementing development measures assuming 'worst-case' scenarios based on a stationary climate that neglects existing IPCC projections. With the added stressor of the unabated and rapid future demographic expansion seen in Asian nations (Table 1), this combination of factors should concern municipal stakeholders, who will decide on developmental plans under uncertain conditions. The provision of useful information to policy makers from a variety of agencies thus would be of importance.

From a climatological standpoint, the continued evolution of extreme-event attribution research can yield useful information when applied to urban resilience. This evolution will very likely occur in several ways: first, by the expansion of weather station records though history with paleoclimate research, and with initiatives such as data rescue (Williamson, 2016) of weather data from ship log books, farmer almanacs and government reports to produce higher-quality records of historical extreme weather events before the twentieth century. Second, robust climate modelling developed from existing research covered in Herring et al. (2014, 2015) can be rapidly applied to present events to detect potential climate change signals; this has already been applied for the August 2016 extreme precipitation event in the United States, which resulted in floods in Louisiana (van der Wiel et al., 2016).

With these research advances, the potential improvements in attribution may provide stakeholders and municipal policy makers with better information – e.g. meteorological conditions leading to drought are actually more frequent and intense than previously thought, as they appear to be in this case study – which could be considered in future urban development that enables adaptation to these potential climate hazards. For instance, the dual strategies of redundancy and anticipatory adaptive design or policy implementation can be applied by municipal authorities in Singapore when explicitly considering the increased probability of future drought affecting its imported water supply. Over time, the projected increase in water supply from technological means (i.e. via recycled and reverse osmosis methods) would substantially lower drought risk in South Johor and Singapore. This redundancy can be augmented by concurrent adaptive actions and policies prioritizing (1) measures reducing local water demand from the residential sector and (2) advances in technology (e.g. increased efficiency from lowered energy consumption of reverse osmosis) related to desalinated water production and supply. The sum of these approaches should increase system resilience to threats of prolonged drought episodes prior to the 2061 expiration of the water treaty with Malaysia.

Other cities have already taken the initiative in applying this strategy of anticipating future conditions using robust climate modelling to yield insights into water management (e.g. simulations of WaterSim for water managers in the US Southwest that will be strongly affected by long-term drought, as discussed by Gober, Sampson, Quay, White, & Chow, 2016), and in subsequently examining relevant measures in policy and urban development to maximize urban resilience.

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References

Agence France-Presse. (2014, March 1). Drought forces Malaysia to expand water rationing around Kuala Lumpur. Retrieved from http://www.abc.net.au/news/2014-02-28/an-drought-forces-malaysia-to-expand-water-rationing-around-kua/5292466

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning, 100*, 341–343. doi:10.1016/j.landurbplan.2011.02.021

Alley, W. M. (1984). The Palmer drought severity index: Limitations and assumptions. *Journal of Climate and Applied Meteorology, 23*, 1100–1109.

AsiaOne. (2013, October 28). PUB to commence work on 36 drainage improvement projects. Retrieved from http://news.asiaone.com/news/singapore/pub-commence-work-36-drainage-improvement-projects?nopaging=1

Beck, F., Bardossy, A., Seidel, J., Muller, T., Fernandez Sanchis, E., & Hauser, A. (2015). Statistical analysis of sub-daily precipitation extremes in Singapore. *Journal of Hydrology: Regional Studies, 3*, 337–358. doi:10.1016/j.ejrh.2015.02.001

Buurman, J., & Babovic, V. (2016). Adaptation pathways and real options analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society, 35*, 137–150. doi:10.1016/j.polsoc.2016.05.002

Cai, W., Santoso, A., Wang, G., Yeh, S.-W., An, S.-I., Cobb, K. M., … Wu, L. (2015). ENSO and greenhouse warming. *Nature Climate Change, 5*, 849–859. doi:10.1038/nclimate2743

Castree, N. (2015). The anthropocene: A primer for geographers. *Geography, 100*, 66–75.

Chow, W. T. L., Chuang, W.-C., & Gober, P. (2012). Vulnerability to extreme heat in metropolitan Phoenix: Spatial, temporal and demographic dimensions. *The Professional Geographer, 64*, 286–302. doi:10.1080/00330124.2011.600225

Chow, W. T. L., Cheong, B. D., & Ho, B. H. (2016). A multimethod approach towards assessing urban flood patterns and its associated vulnerabilities in Singapore. *Advances in Meteorology, 2016*, 7159132. doi:10.1155/2016/7159132

Cook, E. R., Anchukaitis, K. J., Buckley, B. M., D’Arrigo, R. D., Jacoby, G. C., & Wright, W. E. (2010). Asian monsoon failure and megadrought during the last millennium. *Science, 328*, 486–489. doi:10.1126/science.1185188

Cutter, S. L., & Finch, C. (2008). Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences, 105*, 2301–2306. doi:10.1073/pnas.0710375105

Cutter, S. L., Ash, K. D., & Emrich, C. T. (2016). Urban–rural differences in disaster resilience. *Annals of the American Association of Geographers, 106*, 1236–1252. doi:10.1080/24694452.2016.1194740

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orrur, H., … Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management, 146*, 107–115. doi:10.1016/j.jenvman.2014.07.025

de Neufville, R., & Scholtes, S. (2011). *Flexibility in engineering design*. Cambridge, MA: The MIT Press.

Deng, Y., Cardin, M. A., Babovic, V., Santhanakrishnan, D., & Schmitter, P. (2013). Valuing flexibilities in the design of urban water management systems. *Water Research, 47*, 7162–7174. doi:10.1016/j.watres.2013.09.064

Douglass, M. (2016). The urban transition of disaster governance in Asia. In M. A. Miller & M. Douglass (Eds.), *Disaster governance in urbanising Asia* (pp. 13–43). Singapore: Springer.

Geltner, D., & de Neufville, R. (2012). Uncertainty, flexibility, valuation & design: How 21st century information & knowledge can improve 21st century urban development – Part II of II. *Pacific Rim Property Research Journal, 18*, 251–276. doi:10.1080/14445921.2012.11104362

Gober, P., Sampson, D. A., Quay, R., White, D. D., & Chow, W. T. L. (2016). Urban adaptation to mega-drought: Anticipatory water modeling, policy, and planning for the urban Southwest. *Sustainable Cities and Society, 27*, 497–504. doi:10.1016/j.scs.2016.05.001

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., & Briggs, J. M. (2008). Global change and the ecology of cities. *Science, 319*, 756–760. doi:10.1126/science.1150195

Hansen, J., Sato, M., & Ruedy, R. (2012). Perception of climate change. *Proceedings of the National Academy of Sciences, 109*, E2415–E2423. doi:10.1073/pnas.1205276109

Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate, 19*, 5686–5699. doi:10.1175/JCLI3990.1

Herring, S. C., Hoerling, M. P., Kossin, J. P., Peterson, T. C., & Stott, P. A. (2015). Explaining extreme events of 2014 from a climate perspective. *Bulletin of the American Meteorological Society, 96*, S1–S172.

Herring, S. C., Hoerling, M. P., Peterson, T. C., & Stott, P. A. (2014). Explaining extreme events of 2013 from a climate perspective. *Bulletin of the American Meteorological Society, 95*, S1–S96. doi:10.1175/1520-0477-95.9.S1.1

Intergovernmental Panel on Climate Change. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change. (2013). *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.

Jacobi, J., Perrone, D., Duncan, L. L., & Hornberger, G. (2013). A tool for calculating the Palmer drought indices. *Water Resources Research, 49*, 6086–6089. doi:10.1002/wrcr.20342

Leichenko, R. (2011). Climate change and urban resilience. *Current Opinion in Environmental Sustainability, 3*, 164–168. doi:10.1016/j.cosust.2010.12.014

Leong, C. (2016). Resilience to climate change events: The paradox of water (In)-security. *Sustainable Cities and Society, 27*, 439–447. doi:10.1016/j.scs.2016.06.023

Li, X., Meshgi, A., & Babovic, V. (2016). Spatio-temporal variation of wet and dry spell characteristics of tropical precipitation in Singapore and its association with ENSO. *International Journal of Climatology., 36*, 4831–4846. doi:10.1002/joc.4672

Lim, H. S., & Lu, X. X. (2016). Sustainable urban stormwater management in the tropics: An evaluation of Singapore's ABC Waters Program. *Journal of Hydrology, 538*, 842–862. doi:10.1016/j.jhydrol.2016.04.063

Liu, J., Dietz, T., Carpenter, S., Alberti, M., Folke, C., Moran, E., … Taylor, W. M. (2007). Complexity of coupled human and natural systems. *Science, 317*, 1513–1516. doi:10.1126/science.1144004

Marzin, C., Rahmat, R., Bernie, D., Bricheno, L., Buonomo, E., Calvert, D., … Zhang, S. (2015). *Singapore's second national climate change study – Phase 1*. Retrieved from http://ccrs.weather.gov.sg/publications-second-National-Climate-Change-Study-Science-Reports

McBride, J. L., Sahany, S., Hassim, M. E., Nguyen, C. M., Lim, S. Y., Rahmat, R., & Cheong, W. K. (2015). The 2014 record dry spell at Singapore: An Intertropical Convergence Zone (ITCZ) drought. *Bulletin of the American Meteorological Society, 96*, S126–S130. doi:10.1175/BAMS-D-15-00117.1

McSweeney, C., Sahany, S., Marzin, C., Redmond, G., Chan, S., Lee, S. Y., … Sun, X. (2015). Chapter 4: Dynamical downscaling – model evaluation. In C. Marzin, R. Rahmat, D. Bernie, L. Bricheno, E. Buonomo, D. Calvert, … S. Zhang (Eds.), *Singapore's second national climate change study – Phase 1*. Retrieved from http://ccrs.weather.gov.sg/publications-second-National-Climate-Change-Study-Science-Reports

Ministry of the Environment and Water Resources. (2012). *Report on key conclusions and recommendations of the expert panel on drainage design and flood protection measures*. Retrieved from http://www.pub.gov.sg/managingflashfloods/floodResiliencePlan/Documents/fullReport.pdf

National News Bureau of Thailand. (2014, April 4). 38 provinces declared drought disaster zones by DPM; Aid being distributed. Retrieved from http://thainews.prd.go.th/website_en/news/news_detail/WNPOL5704040010009/3/20

Olshansky, R. B. (2009). The challenges of planning for post-disaster recovery. In U. F. Paleo (Ed.), *Building safer settlements. Governance, planning, and responses to natural hazards*. NATO Science for Peace and Security Series, (Vol. 58, pp. 175–181). Amsterdam: IOS Press.

Public Utilities Board. (2015). *The past and the present*. Retrieved from http://www.pub.gov.sg/managingflashfloods/Pages/PastPresent.aspx

Rahman, A. (1981). Chapter 4: Soils. In L. S. Chia, A. Rahman, & D. B. H. Tay (Eds.), *The biophyiscal environment of Singapore* (pp. 89–133). Singapore: NUS Press.

Redman, C. L. (2014). Should sustainability and resilience be combined or remain distinct pursuits? *Ecology and Society, 19*, 37–44. doi:10.5751/ES-06390-190237

Roth, M., & Chow, W. T. L. (2012). A historical review and assessment of urban heat island research in Singapore. *Singapore Journal of Tropical Geography, 33*, 381–397. doi:10.1111/sjtg.12003

Rumbach, A. (2016). Disaster governance in small urban places: Issues, trends, and concerns. In M. A. Miller & M. Douglass (Eds.), *Disaster governance in urbanising Asia* (pp. 109–126). Singapore: Springer.

Shepherd, J. M., Carter, M., Manyin, M., & Burian, S. (2010). The impact of urbanization on current and future coastal precipitation: A case study for Houston. *Environment and Planning B: Planning and Design, 37*, 284–304. doi:10.1068/b34102t

Smith, K. (2004). *Environmental hazards: Assessing risk and reducing disaster*. London: Routledge.

Straits Times. (1963, May 20). Water rationing in Singapore. p. 8. Retrieved from http://eresources.nlb.gov.sg/newspapers/Digitised/Article/straitstimes19630520-1.2.69.1.aspx

Straits Times. (1969, December 12). Worst floods in 35 years cause three deaths and devastation throughout S'pore. p. 5. Retrieved from http://eresources.nlb.gov.sg/newspapers/Digitised/Article/straitstimes19691212-1.2.17.aspx

Tan, K. W. (2006). A greenway network for Singapore. *Landscape and Urban Planning, 76*, 45–66. doi:10.1016/j.landurbplan.2004.09.040

TODAY. (2014, March 8). Water rationing not needed yet, but drills may be held. Retrieved from http://www.todayonline.com/singapore/water-rationing-not-needed-yet-drills-may-be-held

Tortajada, C., Joshi, Y., & Biswas, A. K. (2013). *The Singapore water story: Sustainable development in an urban city state*. Singapore: Routledge.

Tortajada, C., & Joshi, Y. K. (2013). Water resources management and governance as part of an overall framework for growth and development. *International Journal of Water Governance, 1*, 285–306. doi:10.7564/13-IJWG16

Trenberth, K. E. (2012). Framing the way to relate climate extremes to climate change. *Climatic Change, 115*, 283–290. doi:10.1007/s10584-012-0441-5

Trenberth, K. E., Fasullo, J. T., & Shepherd, T. G. (2015). Attribution of climate extreme events. *Nature Climate Change, 5*, 725–730. doi:10.1038/nclimate2657

United Nations. (2015). *World urbanization prospects: The 2014 revision*. Population Division (ST/ESA/SER.A/366). Department of Economic and Social Affairs. Retrieved from https://esa.un.org/unpd/wup/

van der Wiel, K., Kapnick, S. B., van Oldenborgh, G. J., Whan, K., Philip, S., Vecchi, G. A., … Cullen, H. (2016). Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrology and Earth System Sciences*, *21*, 897–921. doi:10.5194/hess-2016-448

Wigley, T. M. L. (2009). The effect of changing climate on the frequency of absolute extreme events. *Climatic Change, 97*, 67–76. doi:10.1007/s10584-009-9654-7

Williamson, F. (2016). Cross-disciplinary working in the sciences and humanities: Historical data rescue activities in Southeast Asia and beyond. *Geoscience Letters, 3*, 31–42. doi:10.1186/s40562-016-0062-3

Yap, K. S. (2013). Urban challenges in South-East Asia. In United Nations (ed.) *Cities of opportunity: Partnerships for an inclusive and sustainable future: Final report of the Fifth Asia-Pacific Urban Forum* (pp.145–162). Bangkok: Clung Wicha. doi:10.13140/2.1.1747.4563

Yow, D. (2007). Urban heat Islands: Observations, impacts, and adaptation. *Geography Compass, 1*, 1227–1251. doi:10.1111/j.1749-8198.2007.00063.x

Zhang, S. X., & Babovic, V. (2011). An evolutionary real options framework for the design and management of projects and systems with complex real options and exercising conditions. *Decision Support Systems, 51*, 119–129. doi:10.1016/j.dss.2010.12.001

Ziegler, A. D., Terry, J. P., Oliver, G. J. H., Friess, D. A., Chuah, J., Chow, W. T. L., & Wasson, R. J. (2014). Increasing Singapore's resilience to drought. *Hydrological Processes, 28*, 4543–4548. doi:10.1002/hyp.10212