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Spatial-temporal changes of compound temperature-humidity extremes in humid subtropical high-density cities: An observational study in Hong Kong from 1961 to 2020

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ABSTRACT

In the humid subtropics, rising temperatures can cause higher humidity via enhanced evaporation which exacerbates heat-related health problems. This study uses multi-station observational data to reveal the spatial-temporal changes of compound temperature-humidity extreme events in Hong Kong during 1961–2020. Based on the 90th and 10th percentiles of temperature and specific humidity, four types of compound events were identified, i.e., Compound Hot and Wet (CHW), Hot and Dry (CHD), Cold and Wet (CCW), and Cold and Dry (CCD) events. Over the past six decades, there has been a significant increase of CHW (+3.45 events/decade) and decrease of CCD (−3.00 events/decade). The greatest increase of CHW was observed during the warm period of the 2010s (+4 events/year/month). Meanwhile, the trends of CHD and CCW were less evident. Spatially, more frequent compound events (especially those with high humidity (CHW and CCW)) were observed in built-up areas compared to rural areas, while the intensity of these events remained similar. The results imply that both regional climate and urban factors contribute to the increase of extreme hot and humid weather. The study generalizes mechanisms for these spatial-temporal changes, and discussed implications for compound extremes management in Hong Kong and other similar cities.

1. Introduction

1.1. Background

A trend of warming climate has been widely observed at the global scale (Berrang-Ford et al., 2011; Masson-Delmotte et al., 2018).

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The observed warming in the latest decade (i.e., 2011–2020) relative to the reference pre-industrial period (i.e., 1850–1900) is between 0.88 °C and 1.21 °C as reported by the Intergovernmental Panel on Climate Change (IPCC, 2021). A warmer climate implies that it is plausible to trigger more heatwaves and temperature extremes. In the humid subtropical climate zone, rising temperatures can result in higher specific humidity in the atmosphere via enhanced evaporation (Willett et al., 2007), and thus further amplifies the severity of heatwaves (Russo et al., 2017).

Heatwaves with high humidity not only affect the physical outdoor environment, but also put extra heat stress on the public, especially on those living in high-density urban settings with a relatively high heat vulnerability (Luo and Lau, 2021; Zhang et al., 2023). High water vapor content in the air weakens the efficiency of evaporative cooling (Tuholske et al., 2021) which can significantly affect thermal comfort during hot periods. Furthermore, research has pointed out that any exceedance of 35 °C of the wet-bulb temperature can evidently reduce humans' heat dissipation capability (Sherwood and Huber, 2010) and cause hyperthermia-related symptoms such as dehydration, heat exhaustion, and heat stroke (Oberlin et al., 2010). Research also linked high humidity in heatwaves with mental health as it might affect brain chemicals that regulate mood (Florido Ngu et al., 2021). Consequently, the compound temperature-humidity extreme events have usually been associated with excess mortality and morbidity (Kravchenko et al., 2013; Matthies and Menne, 2009; Pyrgou et al., 2017). For example, the 1995 Chicago heatwave recorded total mortality of over 700 (Semenza et al., 1996), the 2003 Shanghai heatwave caused 317 mortalities in one day (Tan et al., 2007), the 2015 India and Pakistan heatwave claimed around 3500 lives (Im et al., 2017), and the 2022 England heatwave caused 2800 excess deaths of elderly people (Goodier and Carrington, 2022). It is expected that these heat-related mortality and morbidity will continuously increase in the foreseeable future (Chen et al., 2022).

1.2. *Extreme weather events in Hong Kong*

As a high-density city in the humid subtropical climate zone, Hong Kong is on the trend of rising temperatures and humidity due to both global climate change and urban factors. The city's compact urban setting (He et al., 2022a) and anthropogenic heat emissions (Wang et al., 2018a) lead to a retention of heat and moisture which enhances the Urban Heat Island (UHI) and Urban Moisture Island (UMI) effects. These effects further exacerbate the urban heat stress especially during hot summers. Based on the long-term meteorological observations of the Hong Kong Observatory (HKO, 2022a), the increasing rate of the annual mean temperature in Hong Kong was +0.17 °C per decade (Fig. 1) during 1961–2020. The rising temperatures have caused notable changes of both hot and cold extremes in the city. The number of very hot days (criteria: daily maximum temperature $\geq$ 33 °C) and hot nights (criteria: daily minimum temperature $\geq$ 28 °C) also exhibited a significant increasing trend during 1961–2020. Meanwhile, the number of cold days dropped significantly (criteria: daily minimum temperature $\leq$ 12 °C) during this period (HKO, 2022b). In 2021, there were 61 hot nights and 54 very hot days in Hong Kong, both ranking the highest on record. Furthermore, with a total of 25 hot nights and 21 very hot days, July 2022 set a new record for the highest number of hot nights and very hot days in a single month (HKO, 2022b). Besides rising temperatures, there has also been a significant increasing trend of humidity, e.g., +0.18 g/kg of specific humidity per decade (Fig. 1), in the past decades. This increase was more obviously observed in the city center than peripheral areas according to some recent studies, e.g., Huang et al. (2021).

Given such changing climate in Hong Kong, the consequential health impacts on urban dwellers have attracted critical attention. Previous studies found that stronger heat stress under both hot and cold weather conditions is highly correlated with higher mortality and morbidity in the city (Goggins et al., 2013; Wong et al., 2015). More recent studies found that the higher frequency of extreme events is significantly associated with elevated mortality risk (Ho et al., 2017; Wang et al., 2019a). These studies imply that the health impacts of extreme weather are non-negligible.

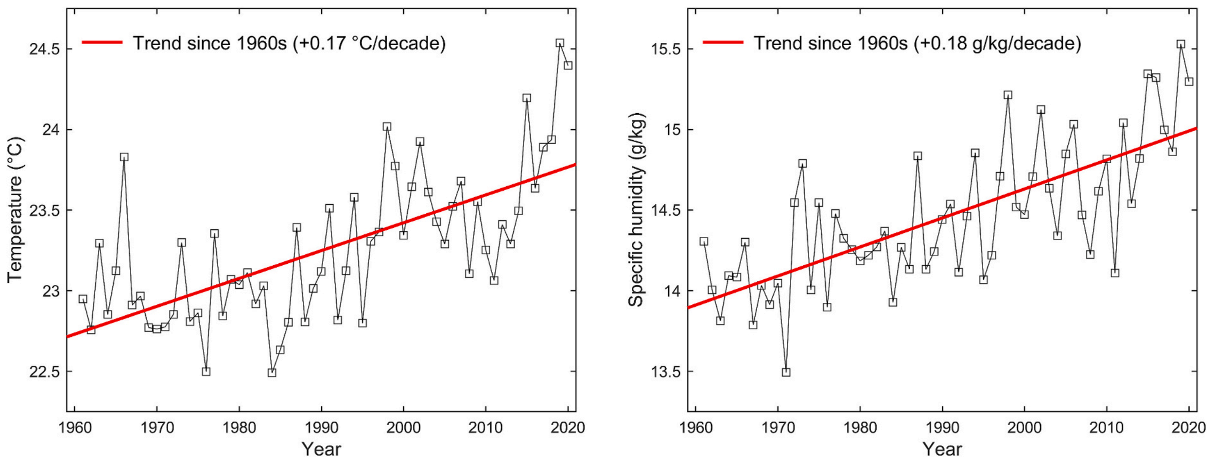

Fig. 1. Increasing trends of annual mean temperature and specific humidity in Hong Kong over 1961–2020, calculated based on the meteorological records of HKO (2022a) (note: the calculation method of specific humidity is introduced in Section 3.2.1).

1.3. Research gaps and objectives

As reviewed in Section 2, a wide range of studies have been conducted on non-compound extreme events of temperature or humidity, yet compound extreme events have been studied much less, especially in humid subtropical high-density cities. Given the high potential health risks of compound temperature-humidity extreme events, it is crucial to understand their variation and tendency, as well as to better mitigate their potential impacts on society. Therefore, in order to fill the knowledge gap, this study aims to conduct a quantitative analysis of the spatial-temporal changes of the single-day compound temperature-humidity extreme events utilizing 60-year observational data in Hong Kong. By better addressing the impact of humidity during temperature extremes, the study could contribute to the improvements of current extreme weather warning system and related weather services, and future adaption action plans for Hong Kong. The methodology and findings could be referred by other cities in the humid subtropical climate zone.

2. Literature review

In this section, we reviewed the previous studies on temperature and/or humidity extreme events to get a state-of-the-art knowledge on the main spatial-temporal changes of these events and identify the research gap. The reviewed studies are classified by compound extreme events and non-compound extreme events (i.e., extreme events that are defined by either temperature or humidity index only) in Table 1. Overview of the current literature is provided in Sections 2.1 and 2.2.

2.1. Studies of non-compound extreme events in the humid subtropics

As shown in Table 1, most of the reviewed literatures focused on the spatial-temporal changes of non-compound extreme events, particularly of extreme heat. Extreme hot events were defined by the daily mean or maximum temperature in the majority of these studies, in which the corresponding thresholds, i.e., absolute thresholds, e.g., 33 °C (Ren et al., 2021), or relative thresholds, e.g., 90th percentile (Liao et al., 2021), were slightly varied. These studies commonly agreed on an increasing tendency of extreme hot events, through either observational data, e.g., Chan et al. (2012), or computer modelling data, e.g., Rusticucci (2012). Particularly, they revealed a significant upward trend of not only frequency, but also intensity and duration of the hot extremes in urban areas, e.g., Founda and Santamouris (2017); Lee et al. (2011a); Luo and Lau (2018). Previous studies also reported enlarged areal extent, prolonged moving distance, and decreased moving speed of the hot extremes at a regional scale, e.g., Luo et al. (2022). Compared with extreme hot events, less attention was paid to extreme cold events in the humid subtropics. Most of the relevant studies reported a notable decrease in the cold extremes, e.g., Xu et al. (2011); Yan et al. (2002); Zhang et al. (2017); Wong et al. (2011), while intensified cold extremes were also reported by a few studies, e.g., Zheng et al. (2022).

Apart from temperature extremes, previous studies also investigated the spatial-temporal changes of humidity extremes. A larger portion of these studies focused on the dry extremes. They reported an upward trend of dry weather in terms of their frequency and intensity in places such as subtropical eastern Australia (Nguyen et al., 2021), southeastern South America (Muza et al., 2009), and Japan (Fujibe et al., 2006). Some studies in east and north China (Luo and Lau, 2019; Wang and Gong, 2010) revealed that rapid urban land expansion may exacerbate the dry effect mainly due to the transformation from vegetation to artificial built-up land cover. A relatively small number of studies focused on the wet extremes. For example, Wang et al. (2021) reported a significant increase in humid weather in coastal subtropical cities. This tendency is consistent with the increasing trend of global specific humidity due to climate change (Willett et al., 2007). However, it should be noted that a number of previous studies also focused on precipitation extremes, e.g., Wong et al. (2011); Fu et al. (2013); Luo et al. (2016); Nath et al. (2017); Zhou et al. (2022). It is known that rainfall might increase relative humidity because of evaporation, but some studies, e.g., Lenderink et al. (2011), have pointed out that the connection between humidity and precipitation is uncertain. In this study, we only consider the humid extremes as the wet extremes, while the precipitation extremes were out of our scope.

2.2. Studies of compound extreme events in the humid subtropics

More recently, research showed increasing concern for the combined effect of extreme temperature and extreme humidity, but the number of relevant studies remains small, as shown in Table 1. Among these studies, compound hot and dry extremes attracted the largest attention due to their potentially adverse impacts on ecosystems and agriculture industries. Higher frequency and intensity have been reported in some subtropical regions in the US (Alizadeh et al., 2020), Australia (Collins, 2021), and China (Liu et al., 2022). However, only a few research studies have focused on other compound extreme types. For example, Xu et al. (2020) revealed that the increasing rate of wet heatwaves was comparable to that of dry heatwaves in terms of both frequency (0.069 versus 0.061 events/decade) and intensity (0.62 versus 0.53 °C/decade) in China in the past decades. McAllister et al. (2022) also exhibited significantly increased frequency of high temperature and high humidity weather in Florida during the summers of 1950–2020. Wu et al. (2019) indicated less frequent co-occurrences of cold extremes and dry extremes in most parts of China.

The literature review revealed that there are relatively less studies on compound temperature-humidity extreme events, especially those with high humidity, however, the combined effect of extreme temperature and extreme humidity should not be overlooked as it has been associated with serious health risks during both hot (Sherwood and Huber, 2010) and cold (Ban et al., 2017) periods, as mentioned in Section 1. Thus, a comprehensive study on the spatial-temporal change of compound temperature-humidity extreme events is urgently needed, especially in high-density urban areas where local human activities such as urbanization may amplify the adverse impact of compound extremes (Basara et al., 2010; Holmer and Eliasson, 1999) and elevate the harm to urban dwellers' living

Table 1
Classification of previous studies on compound temperature-humidity extreme events and non-compound extreme events (i.e., extreme events that are defined by either a temperature or humidity index only) in the humid subtropical climate zone.

Category	Temperature extreme		Humidity extreme		References
	Hot	Cold	Wet	Dry	
Non-compound	●				Chan et al. (2012); Founda and Santamouris (2017); García-Cueto et al. (2019); Hu et al. (2016); Lee et al. (2011a); Liao et al. (2021); Luo and Lau (2017); Luo et al. (2022); Ren et al. (2021); Rogers et al. (2018); Rusticucci (2012); Sachindra et al. (2015); Wang and Gaffen (2001); Wang et al. (2016); Xu et al. (2011); Yan et al. (2002); Zhang et al. (2017); Zhao et al. (2018); Zhou and Ren (2011); Luo and Lau (2018); Lee et al. (2011b)
		●			Xu et al. (2011); Yan et al. (2002); Zhang et al. (2017); Zhao et al. (2018); Zhou and Ren (2011); Wong et al. (2011); Zheng et al. (2022)
			●		Lenderink et al. (2011); Wang et al. (2021)
				●	Zhao et al. (2018); Fujibe et al. (2006); Luo and Lau (2019); Muza et al. (2009); Nguyen et al. (2021); Wang and Gong (2010)
Compound					
	●		●		McAllister et al. (2022); Xu et al. (2020); Zhang et al. (2022)
	●			●	Xu et al. (2020); Alizadeh et al. (2020); Collins (2021); Liu et al. (2022); Zhang et al. (2019); Wu et al. (2019); Zhou and Liu (2018)
		●	●		Zhang et al. (2022)
		●		●	Wu et al. (2019); Zhou and Liu (2018)

environment and health.

3. Methodology

3.1. Data and land use categories

This study utilized daily-averaged meteorological data from four weather stations of the Hong Kong Observatory (HKO, 2022c) to identify compound temperature-humidity extreme events during 1961–2020. To characterize the spatial changes of compound extreme events, weather stations representing four typical surface characteristics (Fig. 2) were selected: 1) the HKO Headquarters station representing the urban area; 2) the King's Park (KP) station representing the urban oasis area; 3) the Tseung Kwan O (JKB) station representing the suburban area; and 4) the Tsak Yue Wu (TYW) station representing the rural area. These four station types were defined by Ren et al. (2021) based on the classification scheme of built and natural Local Climate Zones (LCZs), wherein an area was classified as urban/rural if it was predominantly comprised of built/natural LCZs, and as urban oasis/suburban if it exhibited a mixture of both built and natural LCZs. Throughout the study period, the types of these four stations remained unchanged. Local urbanization rendered buildings taller and denser in the vicinity of the HKO and KP stations, while exerting only a marginal effect on the surface characteristics surrounding the JKB and TYW stations. Additional details of the four selected weather stations are provided in Table 2.

3.2. Definition of compound extreme events

3.2.1. Selection of meteorological parameters

According to the literature review in Section 2, extreme hot and humid weather events can be defined by either meteorological parameters themselves or a heat/thermal index derived from the meteorological parameters. In this study, we used two meteorological parameters, i.e., near-surface air temperature and specific humidity, to indicate the degrees of heat and humidity, respectively. Specifically, the air temperature data were obtained directly from the observational records at the weather stations, while the specific humidity data were converted from the relative humidity data observed at the weather stations by the following equations (Bolton, 1980; Murray, 1966):

$$Q = \frac{622e}{P - 0.378e} \tag{1}$$

$$e = RH \times 6.108exp\left(\frac{17.269T}{T + 237.29}\right) \tag{2}$$

where Q refers to specific humidity (g/kg); e refers to vapor pressure (hPa); RH refers to relative humidity; T refers to air temperature (°C); and P refers to mean sea level pressure (hPa). Distinct from relative humidity, which indicates the humidity relative to its

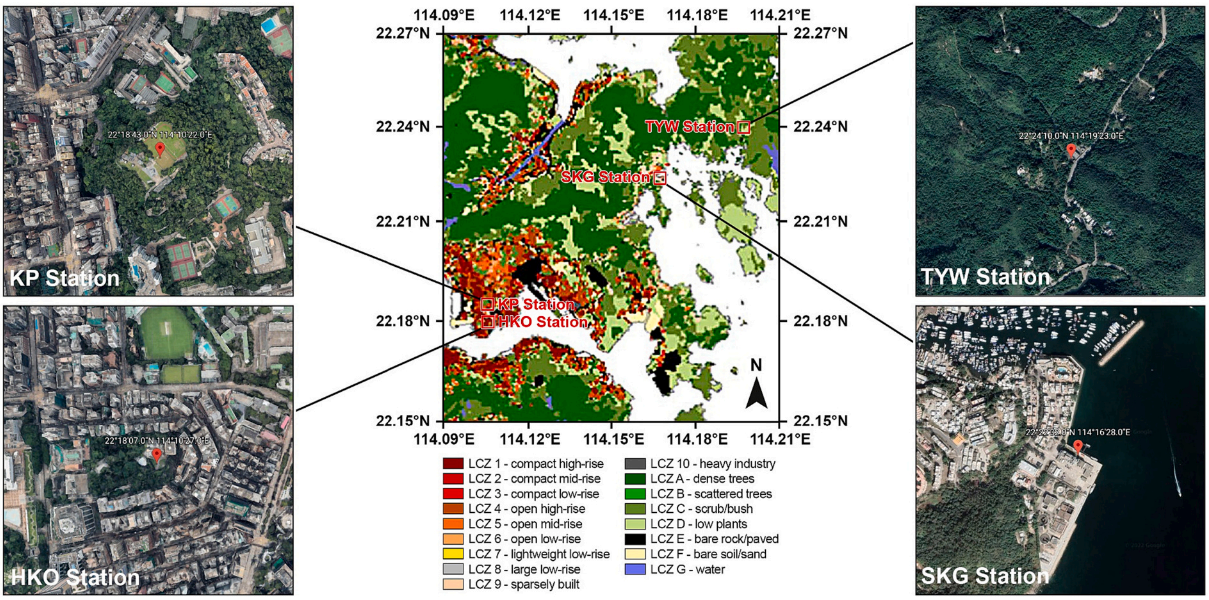

Fig. 2. Surface characteristics near four weather stations presented by the map of built (1−10) and natural (A–G) LCZs (Wang et al., 2018b) and satellite images (Google, 2022).

Table 2
LCZ descriptions (Ren et al., 2021) and operation information (HKO, 2022c) of four weather stations.

Station	Type	LCZs in two radius scopes		Year of first operation
		0–250 m	250–500 m	
HKO	Urban	Open high-rise	Compact high-rise	1884
KP	Urban Oasis	Low plants	Open high-rise	1992
JKB	Suburban	Sparsely built	Sparsely built	1991
TYW	Rural	Dense trees	Dense trees	1995

saturation point at a given temperature, specific humidity is the ratio of water vapor mass to the total moist air parcel mass regardless of temperature. Theoretical and modelling studies have suggested that relative humidity is less sensitive to the warmer climate, and meanwhile a more significant increase in specific humidity has been confirmed (Held and Soden, 2000; Sherwood and Meyer, 2006; Wang et al., 2019b). Since the purpose of this study is to identify humidity change with a changing temperature, we considered specific humidity as a more suitable meteorological parameter than relative humidity.

3.2.2. Identification of compound extreme events

Based on the long-term temperature and specific humidity data from the selected weather stations, compound extreme events were identified in two steps. At the first step, we determined the daily thresholds of temperature and humidity extremes at each station by calculating the 90th and 10th percentiles of temperature (denoted as T_{90P} and T_{10P}, respectively) and specific humidity (Q_{90P} and Q_{10P}). Specifically, the 90th and 10th percentiles of each calendar day were computed from the data within a 31-day moving window centering on the calendar day during a benchmark period. In this study, the benchmark period was determined to be 1996–2010 for two reasons: 1) data over this period was available at all selected stations (Table 2); and 2) this period was prior to the warmest decade on record (i.e., 2011–2020) according to the global datasets from the World Meteorological Organization (WMO, 2021). At the second step, we identified the four types of single-day compound extreme events at each station by comparing the daily-averaged temperature (T) and specific humidity (Q) over the study period (e.g., 1961–2020 at the HKO station) with their 90th and 10th percentiles at the corresponding calendar day over the benchmark period (i.e., 1996–2010). Specifically, a compound hot and wet (CHW) event was identified when $T > T_{90P}$ and $Q > Q_{90P}$; a compound hot and dry (CHD) event was identified when $T > T_{90P}$ and $Q < Q_{10P}$; a compound cold and wet (CCW) event was identified when $T < T_{10P}$ and $Q > Q_{90P}$; and a compound cold and dry (CCD) event was identified when $T < T_{10P}$ and $Q < Q_{10P}$.

3.3. Evaluation of compound extreme events

Two sets of indices were adopted to evaluate the frequency and intensity of the identified compound extreme events. Specifically, we used an indicator to describe the frequency of individual events at individual stations:

$$F_{event} = \frac{N_{event}}{N_{year}} \tag{3}$$

where F_{event} refers to the event frequency; N_{event} refers to the total number of compound extreme events for a specified type within a target calendar period (e.g., the whole year, a specific month, or a specific period); and N_{year} refers to the number of year(s) counted. Particularly, in this study, we defined May to September to be the warm period and November to March to be the cool period in Hong Kong according to historical statistics of very hot days and cold days (HKO, 2022b). A focus was given to the frequency of the hot (CHW and CHD) events during the warm period and the frequency of the cold (CCW and CCD) events during the cool period due to their potentially high health impacts.

Additionally, we used four indices to describe the intensity of temperature and humidity variations of individual events at individual stations:

$$I_{T\_hot} = \frac{\sum_{i=1}^{N_{hot}} (T_i - T_{90P\_i})}{N_{hot}} \tag{4}$$

$$I_{T\_cold} = \frac{\sum_{i=1}^{N_{cold}} (T_{10P\_i} - T_i)}{N_{cold}} \tag{5}$$

$$I_{H\_wet} = \frac{\sum_{i=1}^{N_{wet}} (Q_i - Q_{90P\_i})}{N_{wet}} \tag{6}$$

$$I_{H\_dry} = \frac{\sum_{i=1}^{N_{dry}} (Q_{10P\_i} - Q_i)}{N_{dry}} \tag{7}$$

where I_{T_hot} and I_{T_cold} refer to the average intensity of temperature variation (°C) of the hot (CHW or CHD) and cold (CCW or CCD) events, respectively; I_{H_wet} and I_{H_dry} refer to the average intensity of humidity variation (g/kg) of the wet (CHW or CCW) and dry (CHD or CCD) events, respectively; T_i and Q_i refer to the daily-averaged temperature and specific humidity at an event *i*, respectively; T_{90P_i}, T_{10P_i}, Q_{90P_i}, and Q_{10P_i} refer to T_{90P}, T_{10P}, Q_{90P}, and Q_{10P} at an event *i*, respectively; and N_{hot}, N_{cold}, N_{wet}, and N_{dry} refer to the number of the hot, cold, wet and dry events within a target period, respectively. It should be noted that the values of the four indices were always positive. Based on this definition, a higher I_{T_hot} and I_{T_cold} indicate larger temperature variations at the hot and cold ends, and a higher I_{H_wet} and I_{H_dry} indicate larger humidity variations at the wet and dry ends. The changing trends of the frequency and intensity indices over different periods (e.g., the 1960s (1961–1970) and 2010s (2011−2020)) were estimated by simple linear regression models and their statistical significance were assessed by a non-parametric Mann-Kendall test (Fatichi, 2022).

4. Results and analysis

This section analyzes the changes in four identified types of compound extreme events (i.e., the CHW, CHD, CCW, and CCD events) in Hong Kong. Section 4.1 presents the temporal changes of the events over the past six decades based on the data from the HKO station, which has the longest operation period in the city (Table 2). Section 4.2 presents the spatial changes of the events by cross-comparing the data from all selected weather stations over their overlapping operation periods (i.e., 1996–2020).

4.1. Temporal changes of compound extreme events

4.1.1. Changes of frequency

The frequency changes of the annual compound extreme events during 1961–2020 observed at the HKO station are shown in Fig. 3. In this period, the city experienced a dramatic increase (i.e., from 9.6 events/year in the 1960s to 27.6 events/year in the 2010s) of CHW events, and a substantial decrease (i.e., from 23.8 events/year in the 1960s to 8.5 events/year in the 2010s) of CCD events.

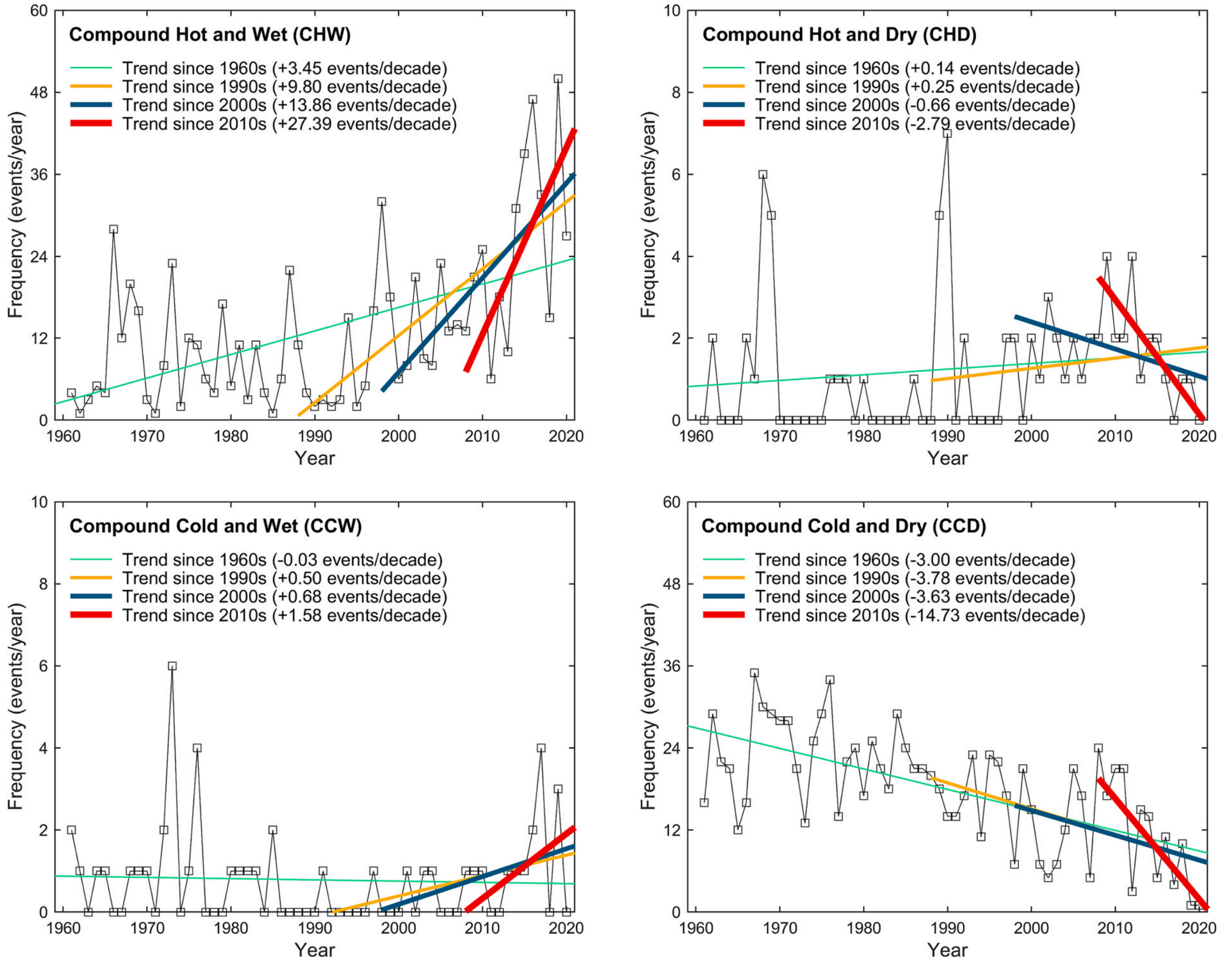

Fig. 3. Frequency of annual compound extreme events in Hong Kong during 1961–2020 (note: the colour lines indicate the corresponding linear trends and their statistical significance test results are listed in Table A1 in the Appendix).

Particularly, there was a continuous acceleration in this trend, where the change rate of CHW and CCD events increased from +3.45 and −3.00 events/decade since the 1960s to +27.39 and −14.73 events/ decade since the 2010s, respectively. In addition, the other two types of events (i.e., the CHD and CCW events) had a lower frequency with relatively large interannual or even interdecadal fluctuations over the study period. Overall, the results reveal that the city has been experiencing more frequent extreme humid weathers during the hot extreme, while extreme dry weathers have become less frequent.

Furthermore, the frequency changes of the monthly compound extreme events over different decades are plotted in Fig. 4. Over the latest decade (i.e., the 2010s), the CHW events had the largest increment during the warm period, especially from May to July where the frequency increased by up to 4 events/year per month more than those in the previous decades. The CCD events had relatively larger reductions during the cool period, where their frequency in the 2010s was over 2 events/year per month less than that in the 1960s. Meanwhile, relatively small changes were observed in the CHD and CCW events over different decades since the annual frequency of these two types of events was low. Overall, the results suggest a greater variation of extreme hot and humid weather during the warm period of the 2010s, while the frequency of extreme cold and dry weather experienced less variability over different periods. The changing trends of event frequency during the warm and cool period are attached in Tables A2 and A3 in the Appendix.

4.1.2. Changes of intensity

In addition to the temporal changes of frequency, analysis was conducted on the temporal changes of intensity of the compound extreme events. Fig. 5 shows the 60-years' annually-averaged intensity of temperature variation of the events in the city. Over this period, the intensity of temperature variation of the CHW events developed in a significant upward trend (i.e., from averagely 0.60 °C in the 1960s to 0.75 °C in the 2010s). Particularly, much faster change rates of the CHW events are observed since the 2000s (i.e., +0.18 °C/decade), tripling that of the overall rate since the 1960s (i.e., +0.06 °C/decade). Meanwhile, the CHD events also

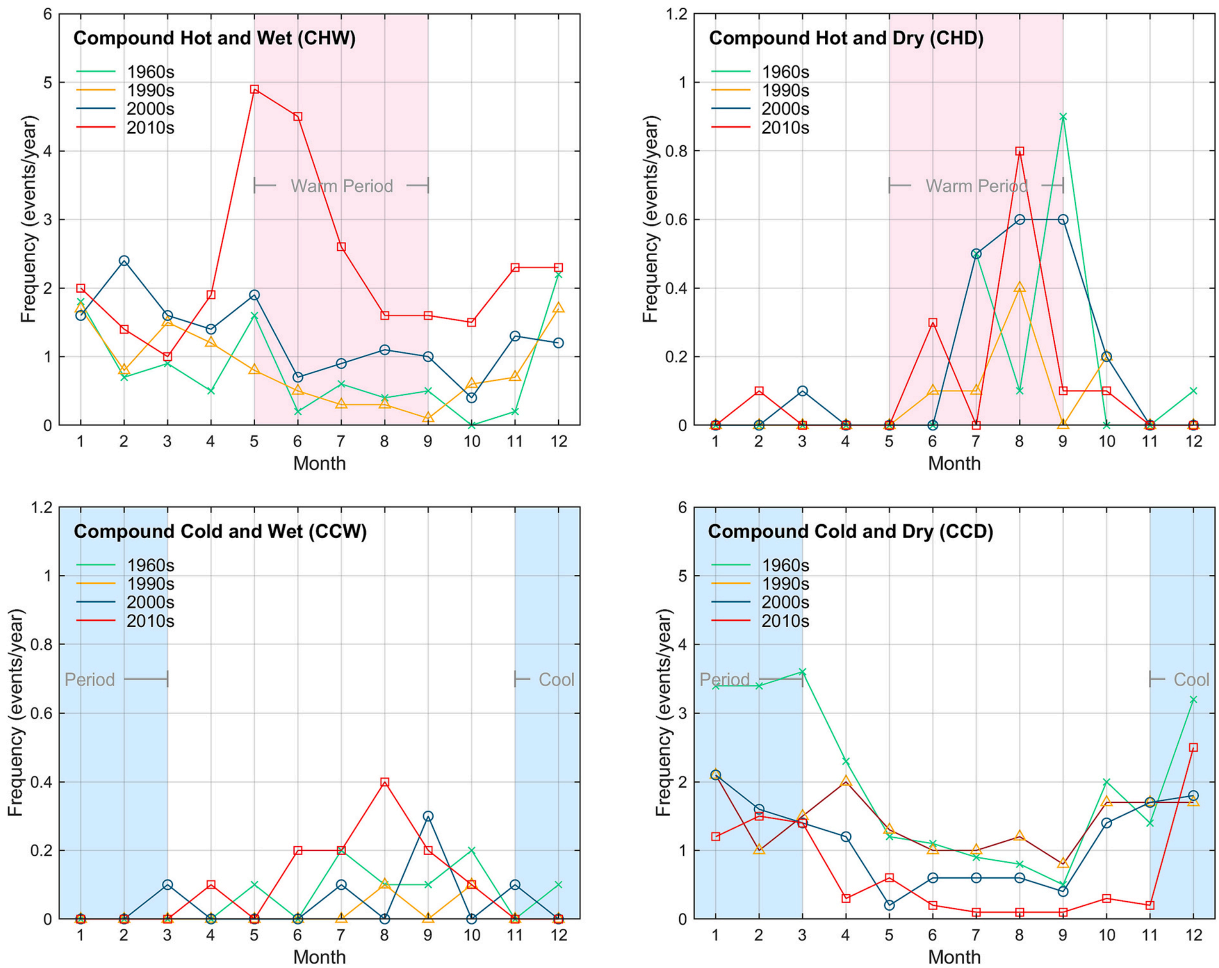

Fig. 4. Frequency of monthly compound extreme events in Hong Kong in 1960s, 1990s, 2000s, and 2010s (note: the pink and blue regions indicate the warm (May to September) and cool (November to March) periods in the city, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

experienced a significant increase in the intensity of temperature variation since 1960s but their interannual fluctuation was large. The change in the cold-related compound events (CCW and CCD) was not significant. The intensity changing trends of periodically-averaged temperature variation of the events during the warm and cool period are attached in Tables B2 and B3 in the Appendix.

The 60-years' annually-averaged intensity of humidity variation of the compound extreme events are shown in Fig. 6, and most of the changes were found insignificant. The intensity changing trends of periodically-averaged humidity variation of the events during the warm and cool period are attached in Tables C2 and C3 in the Appendix. The results in Sections 4.1.1 and 4.1.2 demonstrate that, during the past 60 years, the extreme hot and humid weather events in the city have become more frequent and more intense (in terms of temperature variation) with an increasing change rate, especially during the warm period. Meanwhile, the extreme cold and dry weather events have become less frequent, especially during the cool period.

4.2. Spatial changes of compound extreme events

4.2.1. Changes of frequency

The frequency changes of the annual compound extreme events was cross-compared among the four weather station types, i.e., urban, urban oasis, suburban, and rural areas, as shown in Fig. 7. Overall, the compound extreme events occurred most frequently in the urban area (HKO) and least frequently in the rural area (TYW), and the frequency in the urban oasis and suburban areas (KP and SKG) were in between. Specifically, the wet CHW and CCW events occurred 24% (3.8 events/year) and 75% (0.3 events/year) more frequently in the urban area than the rural area, respectively, over 1996–2020. Particularly, the frequency difference between the urban and rural areas was the largest in the 2010s, reaching 53% (9.6 events/year) in the CHW events and over 100% (1.4 events/year) in the CCW events. Meanwhile, in the case of dry events, the urban area had 1.5 times (0.9 events/year) more frequent CHD events than the rural area, but the CCD events developed in an opposite trend with a slightly lower frequency in the urban area than the rural area.

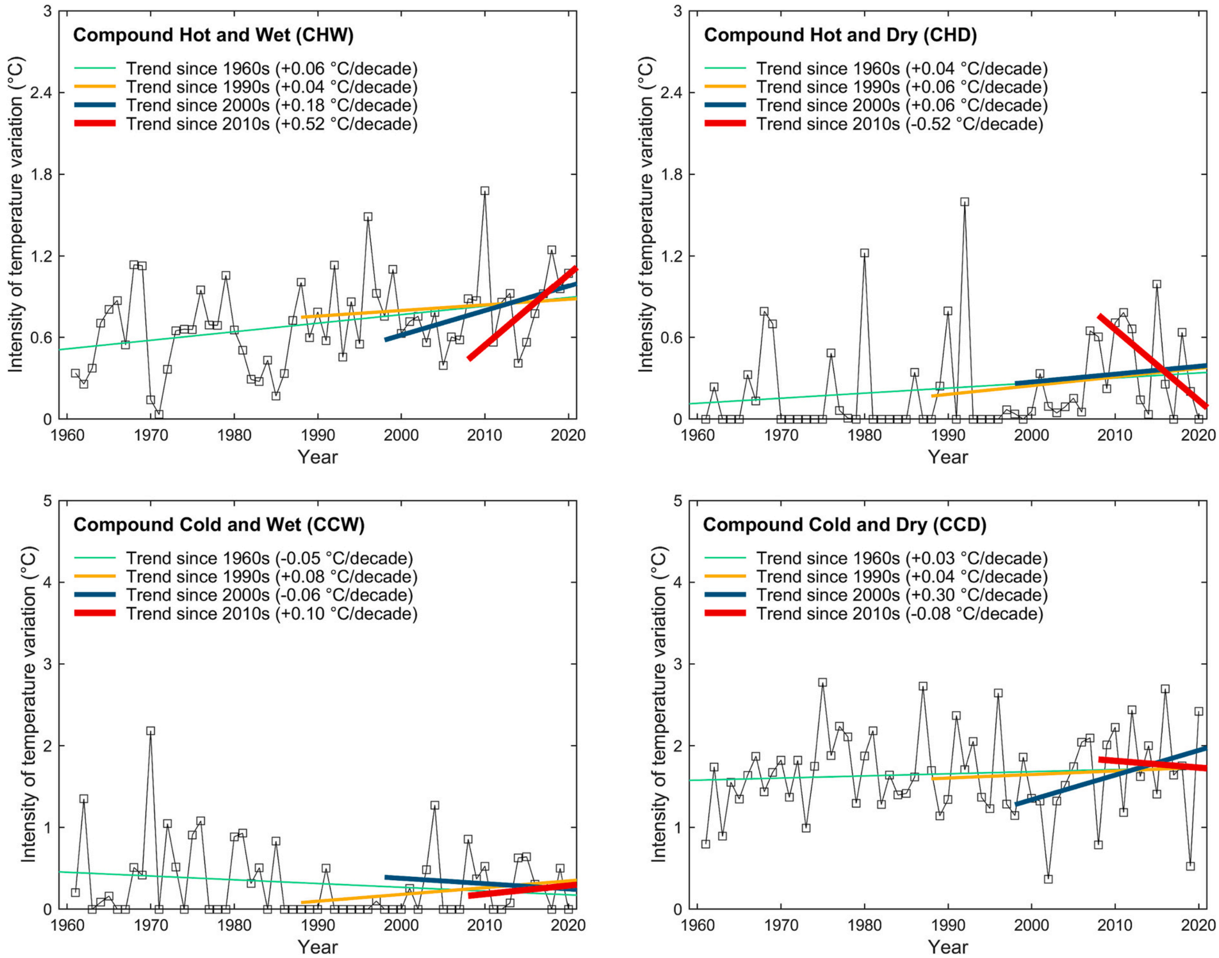

Fig. 5. Intensity of annually-averaged temperature variation of compound extreme events in Hong Kong during 1961–2020 (note: the colour lines indicate the corresponding linear trends and their statistical significance test results are listed in Table B1 in the Appendix).

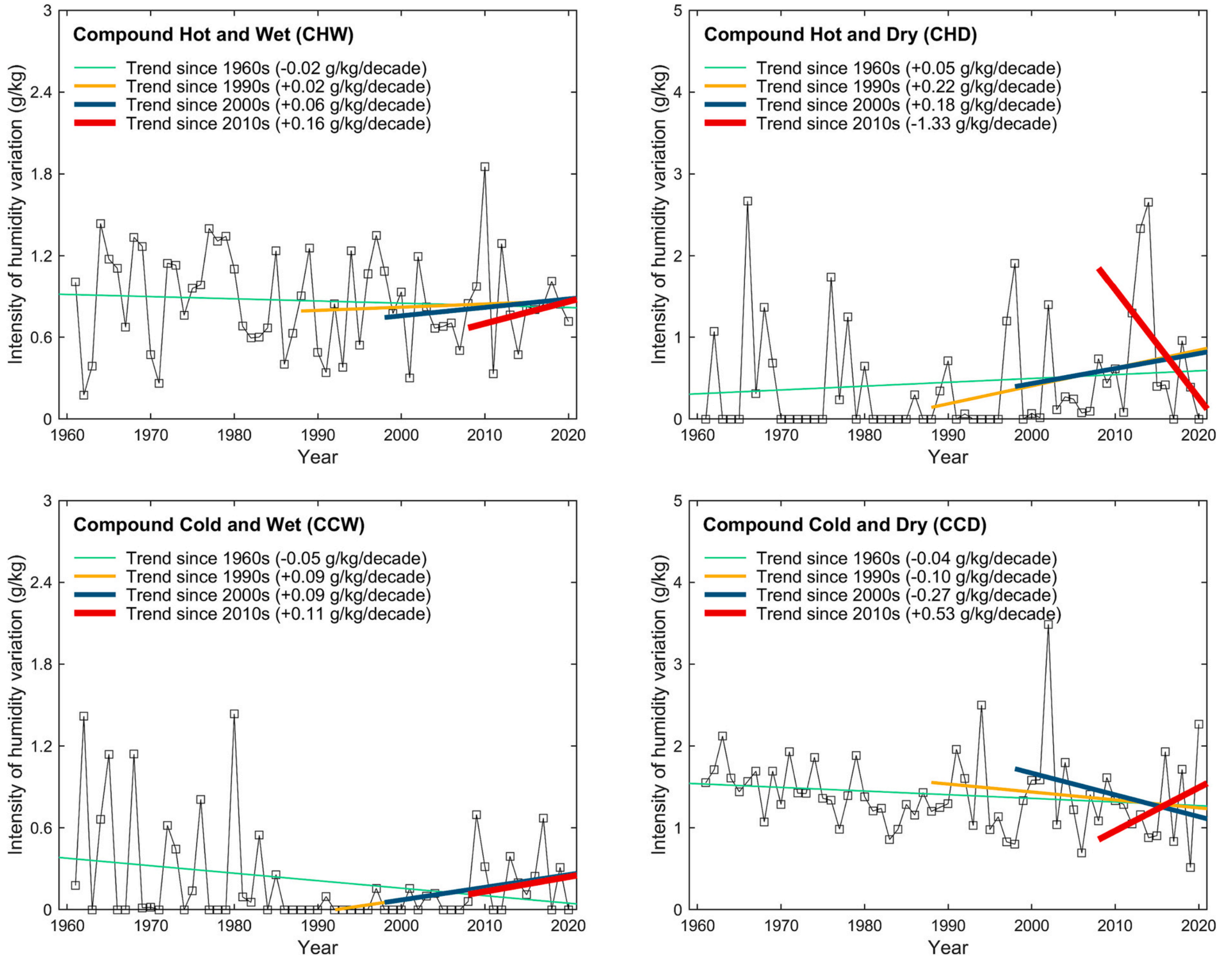

Fig. 6. Intensity of annually-averaged humidity variation of compound extreme events in Hong Kong during 1961–2020 (note: the colour lines indicate the corresponding linear trends and their statistical significance test results are listed in Table C1 in the Appendix).

The results imply that, among the four weather station types, the urban area was most sensitive to the compound extreme events especially those with wet extremes.

Fig. 8 cross-compares the frequency changes of the monthly compound extreme events at four weather stations in the 2010s. An obviously higher frequency (i.e., up to +3 events/year per month) of the CHW events was observed in the built-up areas (i.e., the urban, urban oasis, and suburban areas) than the rural area during the warm period in the city. The larger weather variation in the built-up areas during the warm period suggests that urban factors may contribute more to the change of extreme hot and humid weather when the climate is warmer.

4.2.2. Changes of intensity

The average intensity of temperature variation of the annual compound extreme events at four weather stations is presented in Fig. 9. During the 1996–2020 period, a similar temperature intensity was observed in different areas of the city. The built-up areas overall had a relatively higher intensity than the rural area for most of the compound extreme events, with the exception of CHW events.

The average intensity of humidity variation of the annual compound extreme events at the four weather stations is shown in Fig. 10. Similar to the temperature variation, the humidity variation had similar intensity in different areas of the city during the 1996–2020 period. Compared to the rural area, the built-up areas overall had a lower intensity of the wet (CHW and CCW) events but a higher intensity of the dry (CHD and CCD) events. The results in Sections 4.2.1 and 4.2.2 suggest obvious spatial changes in the frequency of compound extreme events, with the highest frequency in the urban area, while the spatial changes of event intensity were small, with only a slightly higher intensity found in the urban area.

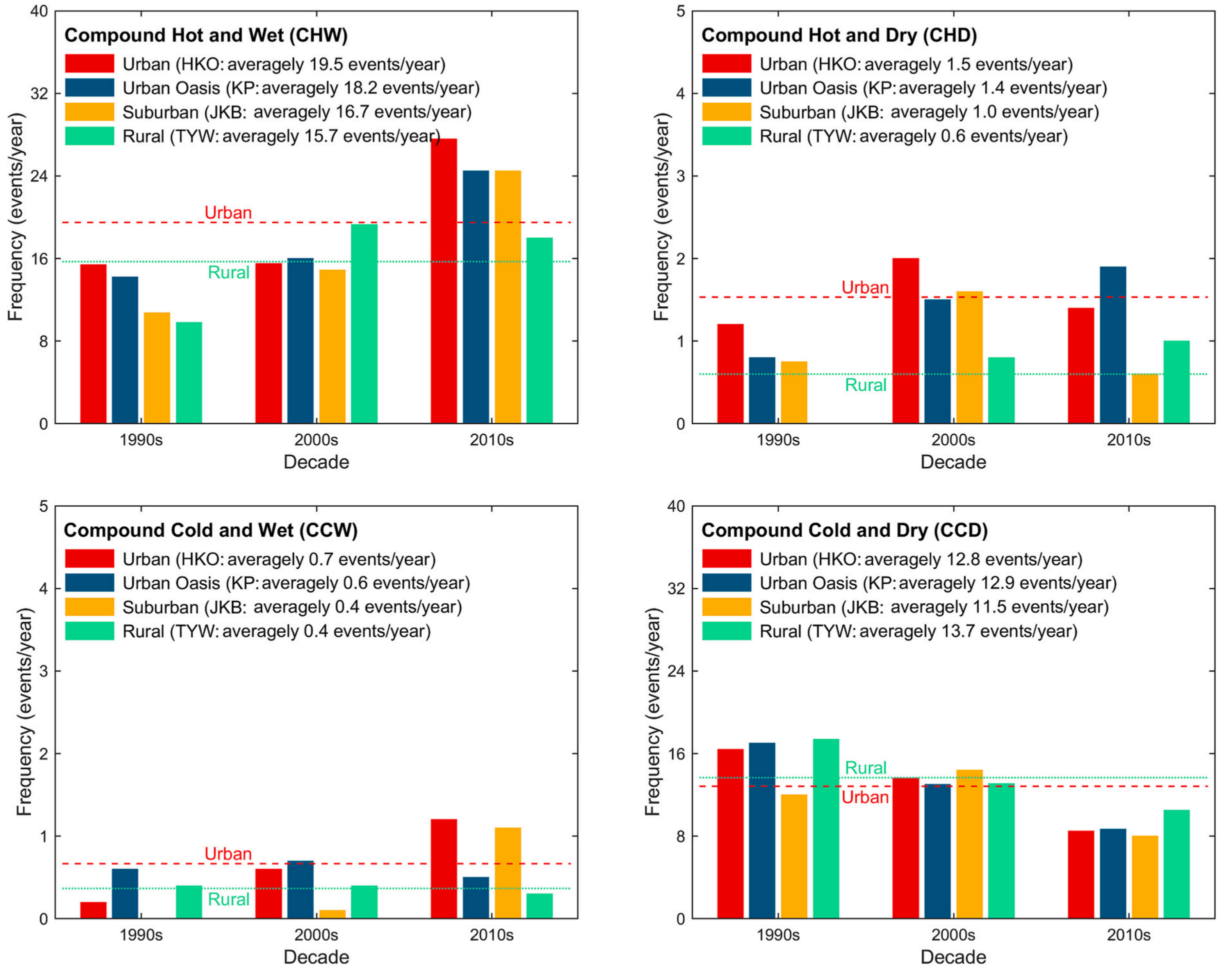

Fig. 7. Frequency of annual compound extreme events at four weather station types over their overlapping period of 1996–2020 (note: the red and green lines indicate the average levels in the urban area (HKO) and rural area (TYW), respectively, during the whole period; and frequency change rates of individual events at individual stations are provided in Appendix A). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

5.1. *Characteristics of the compound extreme event changes in humid subtropical high-density cities*

5.1.1. *Extreme hot and humid events*

Based on the results in Section 4, we found a tendency of higher frequency and intensity (in terms of temperature variation) of extreme hot and humid weather in Hong Kong over the past six decades, indicated by the upward trend of the CHW events and the downward trend of the CCD events. To characterize this tendency of changes in a humid subtropical high-density city, we compared the CHW events in Hong Kong with the humid heatwaves in the whole region of China (i.e., a region with more diverse climates and LCZs) reported by Xu et al. (2020) over a similar period (i.e., 1961–2014). For a fair comparison, the events' change rates in the two datasets were normalized by the numbers of the events in the corresponding periods. The result shows that the normalized frequency change rate of extreme hot and humid events in Hong Kong (i.e., +2.61%/decade) was double that of the national rate (i.e., +1.38%/decade). Meanwhile, the events' normalized intensity change rate of temperature variation in Hong Kong (i.e., +1.24%/decade) was 1.5 times higher than the national rate (i.e., +0.80%/decade). This finding further implies that both the regional climate (e.g., subtropical monsoon climate) and urban factors (e.g., high-density built environment) contribute to the increase and intensification of extreme hot and humid weather events. Their influence might be substantially enhanced over the warm period and in the city center, respectively, according to the results in Sections 4.1 and 4.2.

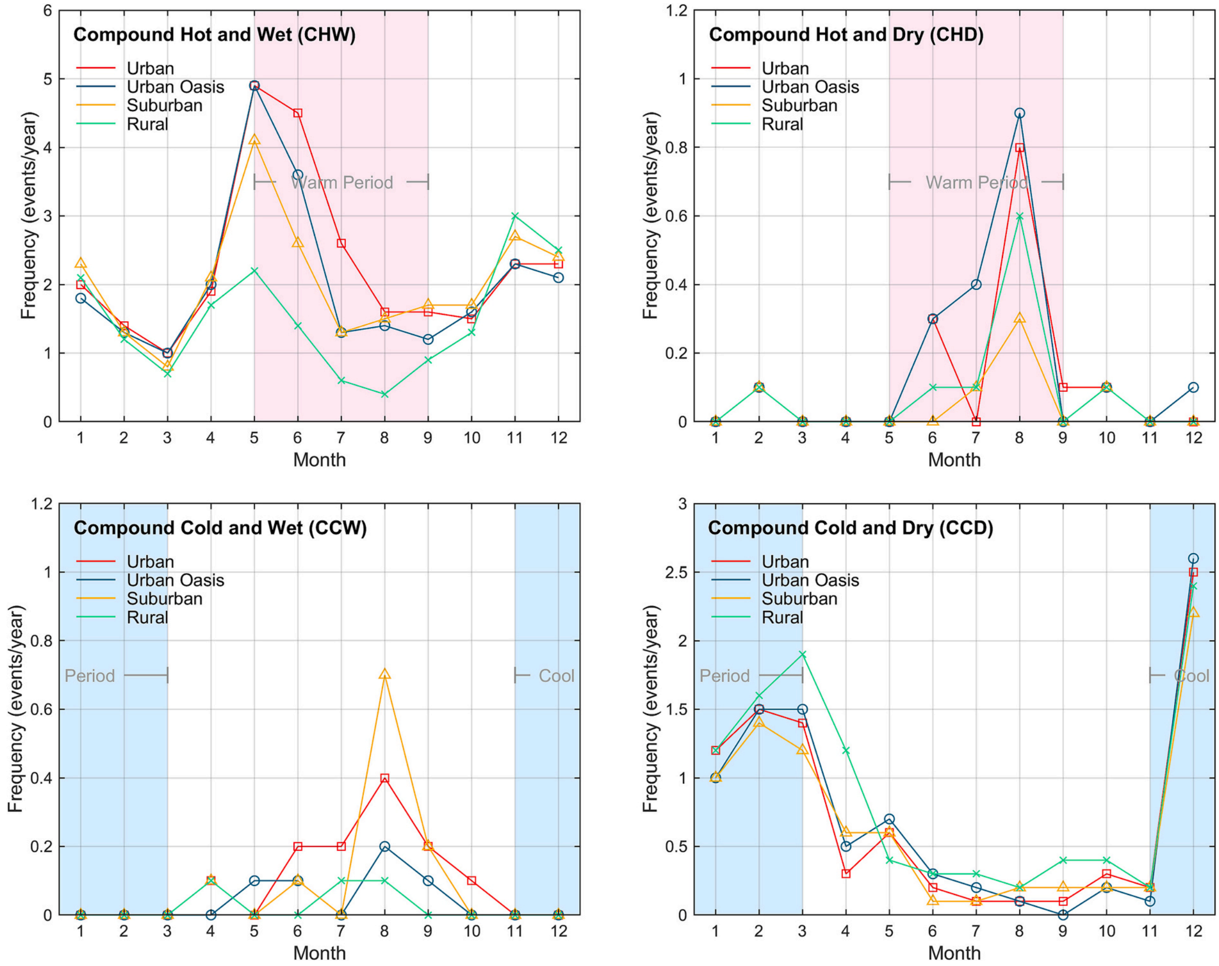

Fig. 8. Frequency of monthly compound extreme events at four weather station types in the 2010s (note: the pink and blue regions indicate the warm (May to September) and cool (November to March) periods in the city, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.1.2. Extreme cold and humid events

The frequency of extreme cold and humid weather events identified in this study was relatively low with obvious interannual and interdecadal fluctuation. Moreover, only a few of these events occurred during the cool period in the city, suggesting that the high-humidity-related health risk in cold extremes was not high. However, the result reveals the relatively frequent extreme cold and humid weather during the non-cool and even warm period, which could cause high variability in the urban climate. Evidence from Zanobetti et al. (2012) and IPCC (2021) has associated a greater climate variability with reduced survivals of elderly people with chronic diseases. However, the health impacts of extreme cold and humid weather events in subtropical high-density cities have not been well addressed by previous studies. Based on the results in this study, the CCW events have demonstrated an upward trend since the 2000s although the data sample size is still insufficient. Thus, more attention should be paid to their tendency in the near future.

5.2. Reasons for the compound extreme event changes in humid subtropical high-density cities

5.2.1. Temporal changes

The temporal changes of the compound extreme events in Hong Kong can be a consequence of the combined effects of local urbanization and global climate change over the decades. In the past 60 years, the city has experienced a continuous dramatic population growth, with the highest increase recorded in the late 1970s (Census and Statistics Department, 2021). It is from this point onward that the urbanization was accelerated and triggered more urban environmental issues, such as the UHI and UMI effects. This urbanization process is fairly consistent with the long-term changing trends of CHW and CCD events in the city. Additionally, global climate change exacerbated the city's overheating especially during 2011–2020 (WMO, 2021). Rising temperatures, meanwhile, enhanced the

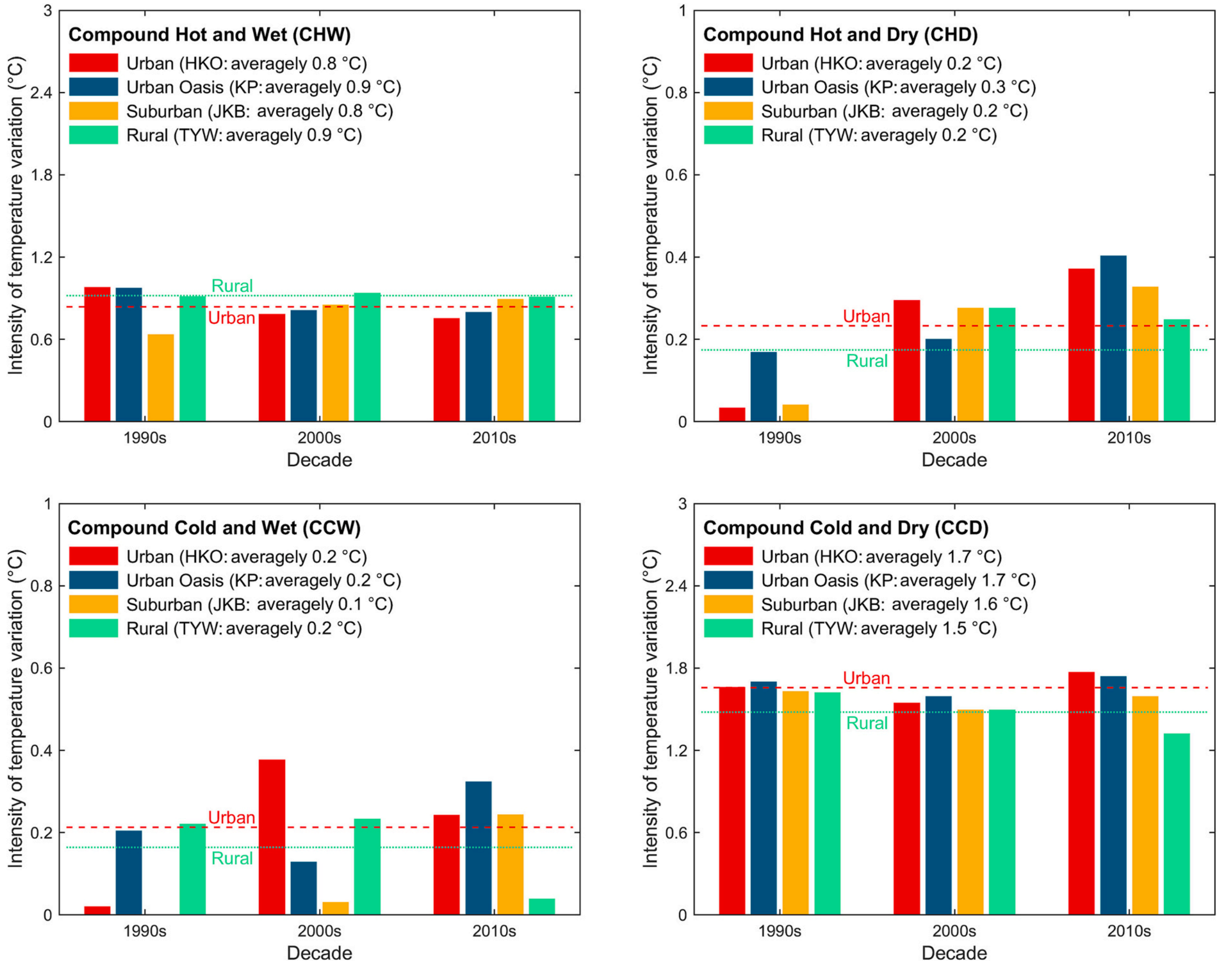

Fig. 9. Intensity of annually-averaged temperature variation of compound extreme events at different weather station types over their overlapping period of 1996–2020 (note: the red and green lines indicate the average levels in the urban area (HKO) and rural area (TYW), respectively, during the whole period; intensity change rates of temperature variation of individual events at individual stations are provided in Appendix B). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

capability of air to hold moisture, and these moist airs were circulated from the sea to land by subtropical monsoons, making the city more humid. This interaction between heat and moisture is most significant during the warm period because of the higher background temperature and stronger UHI effects. The concurrency of higher temperatures and higher humidity might explain the more rapid increase of CHW events and decrease of CCD events in the latest decade. However, it should be noted that some studies (Luo and Lau, 2019; Lin et al., 2020) also associated urbanization with reduced humidity in other cities where the subtropical monsoon climates and land-sea breeze circulations were less prevailing.

5.2.2. Spatial changes

The changes of the compound extreme events were further complicated by the diverse built and natural land covers in the city. Based on the results of this study, more compound extreme events, especially the wet (CHW and CCW) events during the warm period, were identified in the urban area than the rural area. It confirms that the urban factors have affected the changes of the compound extreme events in the city. Some previous studies have revealed that the humidity in an urban area can far exceed that in a rural area (Holmer and Eliasson, 1999; Kuttler et al., 2007; Richards, 2005). Particularly, Wang et al. (2021) observed a higher concentration of air moisture in the city center of Hong Kong than some peripheral areas. They attributed the higher urban humidity to four main reasons: 1) reduced advection of dry air from rural areas induced by higher urban density (Peng et al., 2018); 2) enhanced evapotranspiration induced by higher surface temperatures (Seguin et al., 1994); 3) increased moisture sources induced by more intensive human activities (Kotthaus and Grimmond, 2012); and 4) reduced moisture sinks induced by fewer dewfalls, hygroscopic aerosols, and chemical reactions (Sisterson and Dirks, 1977). These reasons might also explain the tendency that more wet extremes occurred concurrently with hot extremes in the city.

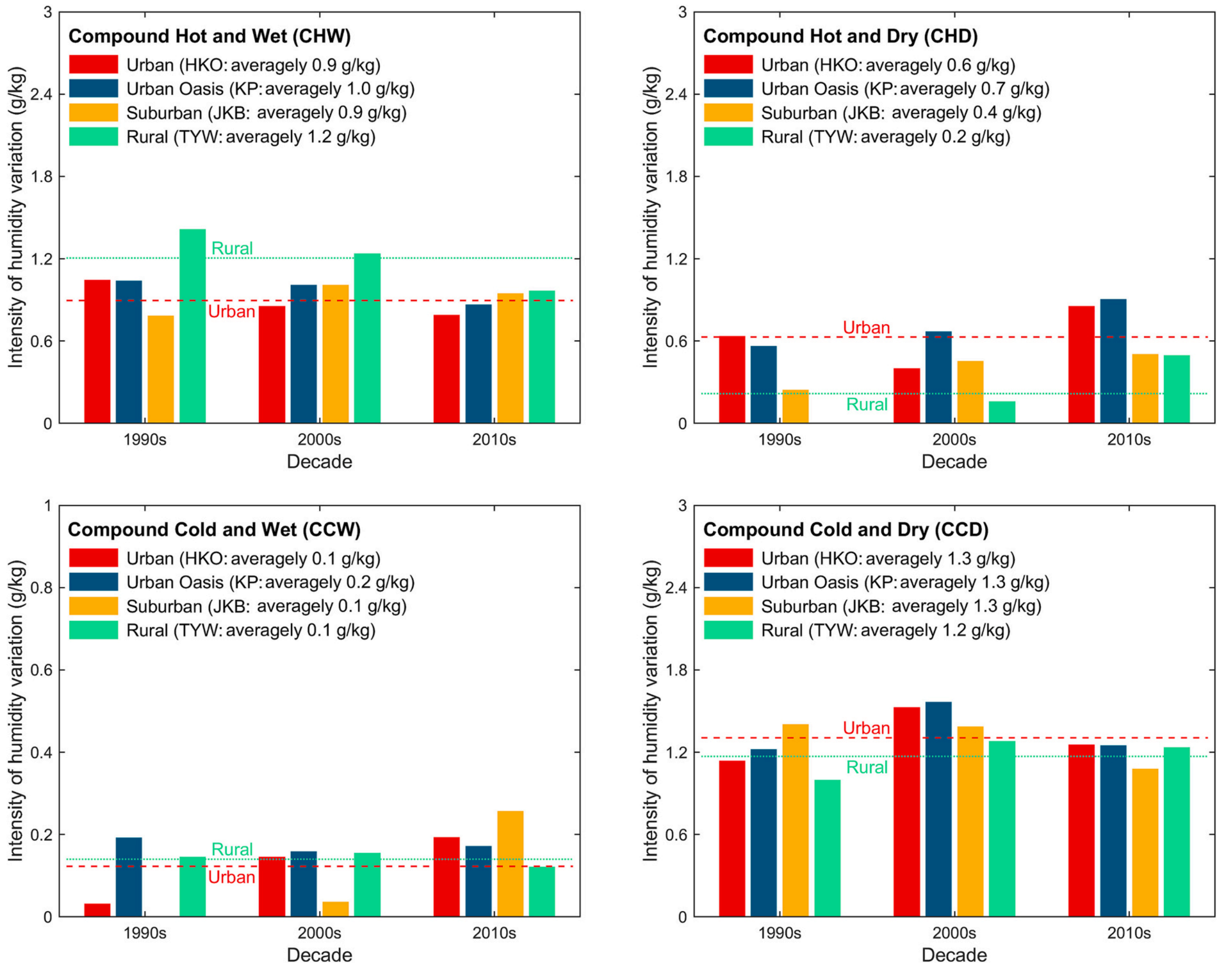

Fig. 10. Intensity of annually-averaged humidity variation of compound extreme events at four weather station types over their overlapping period of 1996–2020 (note: the red and green lines indicate the average levels in the urban area (HKO) and rural area (TYW), respectively, during the whole period; intensity change rates of humidity variation of individual events at individual stations are provided in Appendix C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.3. *Implications for compound extremes' management*

5.3.1. *Factoring compound extremes into the climate change impact assessment*

The consideration of compound extreme events in current climate change impact assessments has been constrained by a dearth of relevant studies, as outlined in Section 2. Identifying the types of compound extreme events and their tendency may contribute to the detection of categorized risks aroused by extreme weather on multiple sectors including health, energy, agriculture, wildfires, and water resources. The significance of our findings, which reveal upward trends of the CHW and CCW events in Hong Kong within the context of climate change (IPCC, 2021; Tong et al., 2017), underscores the urgency of actions. As these trends are anticipated to persist in the foreseeable future, it becomes imperative for future climate change impact assessments to devote special attention to these two types of compound extreme events. By integrating the knowledge of compound extreme events into these assessments, policymakers can craft more targeted strategies to mitigate the corresponding potential risks.

5.3.2. *Enhancement of thermal stress information and warning services*

In response to the call for integrated urban weather, environment, and climate services from the WMO (Baklanov et al., 2018; WMO, 2019), multi-hazard early warning systems, such as a tailor-made compound extreme weather warning system, should be developed to adapt to climate change, strengthen the resilience of cities, and reduce the risk and impact of natural disasters. Locally, since 2000, HKO has been issuing the Cold Weather Warning (CWW) and Very Hot Weather Warnings (VHWW) to alert members of the public to the danger of low body temperatures in cold weather or the risk of heat stroke and sunburn in very hot weather, and to advise the public on relevant preventive measures (HKO, 2021a). Over the years, the CWW and VHWW have in general gained wide public acceptance and understanding in Hong Kong. These warnings also alert relevant government departments to consider the need to take actions, such as the opening of temporary shelters. To enhance the heat stress information services in Hong Kong, HKO and the Chinese University of Hong Kong jointly developed the Hong Kong Heat Index (HKHI) in 2014 for use in the hot and humid sub-tropical climate of Hong Kong. Based on the study results, two reference criteria of HKHI were identified to establish a two-tier approach for the enhancement of the heat stress information service in Hong Kong (HKO, 2014; Lee et al., 2016). With a view to remind the public to prevent discomforts related to very hot weather and pay due attention to health conditions under prolonged heat situations, the HKO further enhanced the relevant precautions associated with the VHWW in 2021 and commenced to issue the "Special Alert on Prolonged Heat" via its website and the "MyObservatory" mobile app in 2022 (HKO, 2021b, 2022d). Our findings of the spatial-temporal changes of compound extremes in Hong Kong could provide useful references for HKO and relevant government departments as well as stakeholders to further enhance the thermal-stress-related weather services and update the climate change adaptation action plans with a view to better address the potential risks and impacts of compound extremes.

5.3.3. Creating community-level intervention strategies

As revealed by a recent modelling study (Chen et al., 2023), heat and moisture can have a complicated distribution in Hong Kong due to its various land use, land cover, topographies, and local circulations (e.g., land-sea breeze circulations). In line with their result, our study reveals different occurrences and changing trends of the CHW, CHD, CCW, and CCD events among four weather stations of different urbanization levels. It implies that future developments of community-level intervention strategies should address such local microclimate variations and take into account the local population and their potential exposure and vulnerability to these compound extremes.

5.3.4. Preparing long-term initiatives for managing compound extremes in urban planning

Climate change has brought about more extreme weather events and caused crisis. Hong Kong is facing a temperature rise and frequent extreme weather phenomena. According to the newly released 'Hong Kong's Climate Change Action Plan 2050' in October 2021, Hong Kong SAR Government has promised to put in extra efforts and take timely actions to combat extreme weather (Bureau, 2021). Currently, researchers have developed urban climate maps as planning tools to predict the frequency of extreme hot events (e.g., Shi et al. (2019)) and their interactions with UHI effects (e.g., Ren et al. (2021)). However, there is a lack of attention on compound temperature-humidity extreme events. It is necessary to comprehensively understand these events and their impact on urban development. As Hong Kong continues to construct more new town developments in the New Territories, it would be critical for town planners and policymakers to consider climate-responsive design strategies in future adaptation action plans to make our city more livable and resilient in the face of a changing climate.

5.3.5. Making references to other cities in the humid subtropical climate zone

The results in this study not only have implications for the management of compound extremes locally, but can also serve as a valuable reference to other high-density cities where the co-occurrence of temperature and humidity extremes is also becoming more frequent and intensive. Hong Kong's experience might help similar cities when they improve or develop their own thermal stress information and warning systems, intervention strategies, and action plans against the adverse impacts of compound extreme events.

5.4. Limitations and further work

This study is known to have limitations. Firstly, we only focused on single-day compound extreme events, while a future study might cover multiple-day compound extreme events with more temporal combinations of temperature and humidity extremes and associate them with mortality and morbidity. Secondly, we suggest to explore diurnal variations of compound extreme events in future studies since the interactions between extreme heat and other urban microclimate factors (e.g., wind (He et al., 2021, 2022b, 2022c)) can be very different in the daytime and nighttime. Finally, the current results rely on data from four representative weather stations, while a recent study (Chen et al., 2023) has revealed a more complicated distribution of temperature and humidity across the city's territory. Therefore, future studies can outline the full picture of spatial changes for compound extreme events and seek to answer two key questions: 1) whether the regional climate or urban factors contribute more to changes in compound extreme events; and 2) whether these changes lead to more urban temperature and humidity extremes.

6. Conclusion

This study makes a pioneering attempt to define compound temperature-humidity extreme events, i.e., Compound Hot and Wet (CHW), Hot and Dry (CHD), Cold and Wet (CCW), and Cold and Dry (CCD) events, and quantify their spatial-temporal changes in Hong Kong using long-term observational data. The main findings are highlighted as follows:

- Significantly more frequent CHW events and less frequent CCD events were identified in Hong Kong over the 1961–2020 period. The trends accelerated continuously, where the CHW events increased by 3.45 and 27.39 events/decade since the 1960s and 2010s, respectively; and the CCD events decreased by 3.00 and 14.73 events/decade correspondingly. This result suggests that the city has been experiencing greater variations of both hot and humid extremes.
- The largest increase of CHW events was observed during the warm period (May to September) in the 2010s and the largest decrease of the CCD events was observed in the cool period (November to March). Their change rate can reach +4 and −2 events/year per month, respectively. This result reveals greater variability in compound extreme weather during the warm period in the latest decade.
- A higher frequency of compound extreme events was found in the built-up areas (i.e., urban, urban oasis, and suburban areas) compared to the rural area. Particularly, the frequency difference between urban and rural areas reached 24% (since the 1960s) and 53% (since the 2010s) for CHW events; and 75% (since the 1960s) and over 100% (since the 2010s) for CCW events. Meanwhile, no notable intensity difference of the compound extreme events was observed in different areas. This result confirms the considerable contribution of urban factors to the changes in compound extreme events.

The results revealed in this study present a general picture of the spatial-temporal changes of compound extreme events in a typical humid subtropical high-density city. They improve the current understanding of the characteristics and mechanism of these compound extreme events. Government agencies, policy makers, and stakeholders in Hong Kong and other similar cities might refer to the results when making their management strategies and future action plans to enhance the cities' resilience to the adverse impacts of global climate change.

CRediT authorship contribution statement

Yueyang He: Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Zixuan Wang:** Methodology, Formal analysis, Writing – original draft. **Hau Man Wong:** Formal analysis, Writing – original draft. **Guangzhao Chen:** Writing – review & editing. **Chao Ren:** Methodology, Formal analysis, Supervision, Writing – original draft, Writing – review & editing, Funding acquisition. **Ming Luo:** Writing – review & editing. **Yuguo Li:** Writing – review & editing. **Tsz-cheung Lee:** Writing – review & editing. **Pak Wai Chan:** Writing – review & editing. **Janice Ying-en Ho:** Writing – review & editing. **Edward Ng:** Methodology, Supervision, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The observational data used in this study are the daily air temperature and relative humidity data from the HKO, which are available at https://www.hko.gov.hk/en/cis/climat.htm.

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Appendix A. Tables of frequency trends

Table A1
Frequency change rates (events/decade) of annual compound extreme events at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CHW	Urban (HKO)	+3.45*	+9.80*	+13.86*	+27.39*
	Urban oasis (KP)		+8.08*	+10.74*	+16.79
	Suburban (JKB)		+9.57*	+10.77*	+15.21
	Rural (TYW)		+3.65	+0.37	+11.88
CHD	Urban (HKO)	+0.14*	+0.25	-0.66	-2.79*
	Urban oasis (KP)		+0.44	-0.15	-1.39
	Suburban (JKB)		-0.00	-0.90*	-0.85
	Rural (TYW)		+0.30	-0.09	-1.21
CCW	Urban (HKO)	-0.03	+0.50*	+0.68	+1.58
	Urban oasis (KP)		+0.07	+0.11	+0.06
	Suburban (JKB)		+0.57*	+0.92	+0.79
	Rural (TYW)		-0.04	-0.08	+0.67
CCD	Urban (HKO)	-3.00*	-3.78*	-3.63	-14.73*
	Urban oasis (KP)		-4.26*	-3.48	-13.88*
	Suburban (JKB)		+0.42	-4.69	-11.88*
	Rural (TYW)		-3.44	-2.41	-13.15*

Table A2
Frequency change rates (events/decade) of the CHW and CHD events during the warm period at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CHW	Urban (HKO)	+1.98*	+6.53*	+8.98*	+13.70*
	Urban oasis (KP)		+5.61*	+6.35*	+7.64
	Suburban (JKB)		+4.43*	+5.58	+4.97
	Rural (TYW)		+1.23	-1.35	+3.45
CHD	Urban (HKO)	+0.10	+0.19	-0.70	-2.55
	Urban oasis (KP)		+0.26	-0.34	-1.70
	Suburban (JKB)		-0.12	-0.99*	-0.61
	Rural (TYW)		+0.20	-0.17	-0.97

Table A3
Frequency change rates (events/decade) of the CCW and CCD events during the cool period at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CCW	Urban (HKO)	-0.03	+0.04	-0.03	+0.00
	Urban oasis (KP)		-0.04	-0.03	+0.00
	Suburban (JKB)		+0.02	-0.01	+0.00
	Rural (TYW)		-0.05	-0.01	+0.00
CCD	Urban (HKO)	-1.71*	-0.56	-1.32	-10.42
	Urban oasis (KP)		-0.16	-1.28	-11.33
	Suburban (JKB)		+0.67	-1.97	-10.55
	Rural (TYW)		-0.06	-1.31	-11.58*

Appendix B. Tables of intensity trends for temperature variation

Table B1
Intensity change rates (°C/decade) of annually-averaged temperature variation of compound extreme events at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CHW	Urban (HKO)	+0.06*	+0.04	+0.18*	+0.52*
	Urban oasis (KP)		+0.00	+0.09	+0.39
	Suburban (JKB)		+0.27*	+0.14*	+0.23
	Rural (TYW)		+0.05	+0.09	+0.27
CHD	Urban (HKO)	+0.04*	+0.06*	+0.06	-0.52
	Urban oasis (KP)		+0.17*	+0.20	+0.28
	Suburban (JKB)		+0.16*	+0.11	-0.05
	Rural (TYW)		+0.07	-0.06	+0.00
CCW	Urban (HKO)	-0.05	+0.08	-0.06	+0.10
	Urban oasis (KP)		+0.10	+0.16	-0.27
	Suburban (JKB)		+0.11	+0.16	-0.13
	Rural (TYW)		-0.08	-0.11	+0.07
CCD	Urban (HKO)	+0.03	+0.04	+0.30	-0.08
	Urban oasis (KP)		+0.08	+0.19	-0.28
	Suburban (JKB)		+0.30	+0.14	-0.34
	Rural (TYW)		-0.13	-0.08	-0.47

Table B2
Intensity change rates (°C/decade) of periodically-averaged temperature variation of the CHW and CHD events during warm period at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CHW	Urban (HKO)	+0.05*	+0.13*	+0.03	+0.05
	Urban oasis (KP)		+0.15*	+0.02	-0.38
	Suburban (JKB)		+0.21*	-0.01	-0.53
	Rural (TYW)		+0.20*	+0.09	+0.04
CHD	Urban (HKO)	+0.05*	+0.05	+0.03	-0.49
	Urban oasis (KP)		+0.11	+0.10	+0.02
	Suburban (JKB)		+0.09	+0.03	-0.03
	Rural (TYW)		+0.03	-0.12	-0.04

Table B3
Intensity change rates (°C/decade) of periodically-averaged temperature variation of the CCW and CCD events during cool period at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CCW	Urban (HKO)	-0.03	+0.02	-0.01	+0.00
	Urban oasis (KP)		+0.00	-0.01	+0.00
	Suburban (JKB)		+0.01	-0.06	+0.00
	Rural (TYW)		-0.02	-0.04	+0.00
CCD	Urban (HKO)	-0.06	-0.14	+0.34	-0.07
	Urban oasis (KP)		+0.09	+0.26	+0.18
	Suburban (JKB)		+0.43	+0.31	+0.21
	Rural (TYW)		-0.15	+0.20	+0.26

Appendix C. Tables of intensity trends for humidity variation

Table C1
Intensity change rates (g/kg/decade) annually-averaged humidity variation of compound extreme events at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CHW	Urban (HKO)	-0.02	+0.02	+0.06	+0.16
	Urban oasis (KP)		-0.05	-0.04	+0.02
	Suburban (JKB)		+0.25*	+0.07	+0.38
	Rural (TYW)		-0.19	-0.11	-0.16
CHD	Urban (HKO)	+0.05*	+0.22*	+0.18	-1.33
	Urban oasis (KP)		+0.25	+0.11	-0.59
	Suburban (JKB)		+0.22*	+0.21	-0.06
	Rural (TYW)		+0.24	+0.22	-0.19
CCW	Urban (HKO)	-0.05	+0.09*	+0.09	+0.11
	Urban oasis (KP)		+0.04	+0.09	+0.15
	Suburban (JKB)		+0.12	+0.18	-0.07
	Rural (TYW)		-0.03	-0.06	+0.29
CCD	Urban (HKO)	-0.04*	-0.10	-0.27	+0.53
	Urban oasis (KP)		-0.06	-0.35	+0.24
	Suburban (JKB)		+0.10	-0.31	+0.07
	Rural (TYW)		+0.11	+0.01	+0.42

Table C2
Intensity change rates (g/kg/decade) of periodically-averaged humidity variation of the CHW and CHD events during warm period at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CHW	Urban (HKO)	+0.01	+0.21*	+0.11	-0.26
	Urban oasis (KP)		+0.20	-0.00	-0.55
	Suburban (JKB)		+0.13	-0.08	-0.03
	Rural (TYW)		-0.11	-0.52	-0.35
CHD	Urban (HKO)	+0.01	+0.17	+0.07	-0.65
	Urban oasis (KP)		+0.15	+0.01	-0.04
	Suburban (JKB)		+0.09	+0.13	+0.20
	Rural (TYW)		+0.14	+0.10	-0.03

Table C3
Intensity change rates (g/kg/decade) of periodically-averaged humidity variation of the CCW and CCD events during cool period at four weather station types (* is marked at the significant level of 0.05).

Event	Class (station)	Since 1960s	Since 1990s	Since 2000s	Since 2010s
CCW	Urban (HKO)	-0.03	+0.02	-0.02	+0.00
	Urban oasis (KP)		+0.01	-0.03	+0.00
	Suburban (JKB)		+0.01	-0.01	+0.00
	Rural (TYW)		-0.02	-0.03	+0.00
CCD	Urban (HKO)	-0.02	+0.03	-0.22	+0.33
	Urban oasis (KP)		+0.17	-0.09	+1.12
	Suburban (JKB)		+0.19	-0.25*	+0.55
	Rural (TYW)		+0.36	+0.36	+0.88

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