Journal of the Meteorological Society of Japan

EARLY ONLINE RELEASE

The DOI for this manuscript is
DOI:10.2151/jmsj.2022-023
J-STAGE Advance published date: February 8th, 2022
The final manuscript after publication will replace the preliminary version at the above DOI once it is available.

Observed increase of urban extreme rainfall as surface temperature rise: the Jakarta case

Siswanto

Agency for Meteorology, Climatology, and Geophysics of the Republic of Indonesia (BMKG) and Institute for Environmental Studies, Vrije Universiteit Amsterdam, The Netherlands,

Gerard van der Schrier

Royal Netherlands Meteorological Institute (KNMI), The Netherlands,

and

Bart van den Hurk

Deltares, Delft, The Netherlands and Institute for Environmental Studies, Vrije Universiteit Amsterdam, The Netherlands

January 27, 2022

Corresponding author: Siswanto, Center for Applied Climate Information and Services, The Agency for Meteorology, Climatology, and Geophysics of Republic of Indonesia, Jl. Angkasa 1 No. 2 Kemayoran Jakarta.

E-mail: *siswanto@bmkg.go.id*

Abstract

Sub-daily extreme precipitation in Jakarta exhibits trends related to local temperature, seasonal tropical monsoon circulations, and other environmental drivers. Analysis of 81 years of hourly rainfall between 1900 – 2010 shows a significant increase of about doubling the number of short-duration rainfall events in the wet season. In recent decades, rainfall is found to be higher in intensity and shorter in duration relative to preceding decades. These short-duration rain showers develop typically between afternoon and late night or during early morning hours. Changing short-duration rainfall characteristics throughout the last century are partly attributed to changes in the surface environment of urban Jakarta. A recent temperature increase and land surface drying in the city, in combination with a small increase of the atmospheric moisture content, promote intensified atmospheric convection. A combination of rain gauge data with upper-air observations collected during 2002 – 2016 reveals that surface warming in the urbanized city accompanied by enhanced availability of moisture results in an increase of convective available potential energy (CAPE), which contributes to enhanced intense precipitation. Super Clausius-Clapeyron scaling (CC) of high-intensity rainfall is attributed to high near-surface temperature and atmospheric moisture content in the morning. This super CC scaling is present in a relatively small range of surface temperature values. Results of this study are in agreement with earlier findings exploring the intensification of extreme morning precipitation and a temporal shift of the diurnal convective maximum from late afternoon to late night/early morning in response to local warming. For a delta city such as Jakarta with abundant convection and heavy precipitation, a well-maintained rainfall database is crucial to assist urban flood early warning.

Keywords: climate change, sub-daily rainfall extremes, urban, temperature, moisture, clausius-clapeyron, convection, thermodynamics, dynamics, tropical rainfall, Jakarta

1. Introduction

In most climate regions of the planet, extreme precipitation is expected to increase non-uniformly with anthropogenic global warming (IPCC, 2021). An increase of the atmospheric temperature by 1°C increases the water holding capacity of an air parcel by about 7% (Trenberth, 2011), according to the so-called Clausius-Clapeyron relationship, expressing the relation between the moisture-holding capacity of the atmosphere, temperature, and pressure (Lenderink and van Meijgaard, 2010; O' Gorman, 2015). Model projections show that global mean precipitation increases with temperature at a rate lower than the atmospheric moisture increase (Held and Soden, 2006; IPCC, 2013), and is estimated to be about 1 – 3% per degree of global warming (Wentz et al., 2007; Lambert et al., 2008). Uncertainties of increases of frequency and intensity of extreme precipitation are considerable and regionally varying (Meehl et al., 2007; Hardwick Jones et al., 2010).

Using hourly observations of temperature and precipitation, Lenderink and van Meijgaard (2008) showed that in the Netherlands relatively mild precipitation extremes (the 90th- percentiles) increase with temperature at a rate close to Clausius-Clapeyron (1CC, approximately ~7%/°C). For stronger extremes (99th-percentiles) a super-CC relation with temperature exists (almost 2CC, or approximately ~14%/°C). Similar results were found for Belgium and Switzerland (Lenderink and van Meijgaard, 2010). A comparison between The Netherlands and Hongkong showed that the scaling closely follows a 2CC for higher percentiles in both climate zones, but in Hongkong, this scaling is confined to dew point temperatures below 23°C (Lenderink et al., 2011). Similar observations were explored for other regions, e.g., in Germany (Haerter and Berg, 2009; Berg et al., 2013), Australia (Hard- wick Jones et al., 2010), Japan (Utsumi et al., 2011), and America (Shaw et al., 2011). The intensity-dependent CC scaling is generally less explicit for daily precipitation (Lenderink and van Meijgaard, 2008), and even negative scaling relationships between precipitation extremes and temperature were found at most stations over mainland China (Miao et al., 2016).

Although in the extra-tropics intensified precipitation extremes are observed in response to a temperature increase following thermodynamic concepts, the sensitivity of precipitation extremes to warming in the tropical regions remains uncertain. This is probably related to specific feedbacks associated with the strong convection (O’Gorman, 2015), resulting from contributions of dynamical or microphysical processes (Muller and Takayabu, 2020). The contribution of dynamical processes mainly consists of changes in atmospheric (vertical) motions. In addition, feedback on microphysical processes leads to altered precipitation efficiency (Muller and Takayabu, 2020). These feedbacks are suggested to be at least partly caused by responses to local warming (Lau et al., 2017; Lutsko and Cronin, 2018; Muller and Takayabu, 2020).

Over Indonesia, increasing trends of both frequency and intensity of extreme daily precipitation have been found in the last decades, together with spatially coherent increasing trends of various temperature indices (Supari et al., 2017). For Jakarta, a century-long record of high-quality data was used (Siswanto et al., 2016). Jakarta’s temperature has increased at a rate exceeding the global mean temperature over the past century, in response to both global warming and the rapid urbanisation (Siswanto et al., 2016). The heaviest 1% of all precipitation events also exhibits an increasing trend, particularly during the wet season. These events have become roughly 2.4 times more likely over the last 115 years (Siswanto et al., 2015). In contrast, the annual mean precipitation does not display a strong trend.

Torrential rain events of >200 mm day^{-1} are rare in the region and are usually associated with major flood events. As an example of a corresponding extreme precipitation event, extensive flooding struck the city on the 2020 new year’s eve after a record-breaking daily extreme precipitation of 377 mm recorded at Halim PK Airport. Similar rainfall events led to the February 2015 and January 2014 Jakarta flooding. Frequently the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) is asked to provide guidance on changes in precipitation extremes, its relation to urban flooding events, the impact of climate change, and urbanisation on these trends.

These extreme events are usually generated from rapidly developing large-scale convective systems induced by particular regional atmospheric circulation features. A strong background Asian monsoon system, orographic lifting, proximity of tropical cyclones (or tropical low-pressure system), equatorial atmospheric waves, or patterns with high regional sea surface temperatures (SSTs) may enhance the formation of extreme convection over Jakarta. These confounding factors are responsible for a strong seasonal to inter-annual variability of the occurrence frequency and intensity of Jakarta's extreme precipitation events. At shorter multi-day to weekly time-scales, the Asian monsoon activity is governed by the emergence of cold surges (CS) or cross-equatorial northerly surges (CENS), and the presence of the Intertropical Convergence Zone (ITCZ), which may coincide with CS or CENS events. The Madden-Julian Oscillation (MJO) is the main source of variability at the sub-seasonal time-scale, while on the inter-annual time-scale the well-known El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are dominant (see e.g., Chang et al., 2005; Hattori et al., 2011; Wu et al., 2013; Koseki et al., 2013; Siswanto et al., 2015; Mori et al., 2018; Lestari et al., 2019). Under favourable atmospheric conditions, convective clouds develop at high altitudes, often as a spin-off from a mesoscale convective system (Nuryanto et al., 2019). This occasionally generates large torrential downpours with repeated showers that can last up to a few hours.

Observation-based relationships between sub-daily precipitation and temperature may contain useful guidance on the sensitivity of tropical precipitation extremes to local warming. Sub-daily precipitation extremes show a stronger response to changes in local atmospheric temperature changes than daily-mean precipitation (Westra et al., 2014; Barbero et al., 2019). These temperature changes may arise from both urbanisation and global warming, and thus both trends have the ability to affect the local precipitation characteristics (Mc-Carthy et al., 2010) in the tropical and energetic monsoon region of Jakarta.

This paper analyses the precipitation-temperature scaling for the Jakarta area. We assess trends in sub-daily duration, intensity, frequency, and timing of rainfall, and relate it to surface conditions (near-surface temperature, urbanisation, atmospheric moisture, and convection characteristics) and large-scale climatic oscillations. We use more than 100 years of daily and more than 80 years of hourly observational records from Jakarta Observatory. In addition, 15 years of upper air sounding observations collected between 2002 and 2016 at Soekarno-Hatta Int' l Airport are included in the analysis. This long observational record contributes to the statistical robustness of the assessment of the drivers of extreme precipitation and long-term trends therein.

2. Data and Methods

The main dataset used in this study consists of hourly surface measurements at Batavia (Jakarta) Observatory between the period of 1900 – 1980 and 2000 – 2010. This study does not analyse the period 1981-1999 due to missing digitised data, although observations were continued for this period (e.g., daily/pentad rainfall amount is available). The dataset is built from old Jakarta Observatory yearbook archives stored at the Royal Netherlands Meteorological Institute (KNMI) and BMKG. Digitisation activities took place under the joint BMKG/KNMI project Digitisasi Data Histories (DiDaH) and successfully rescued a-130 years-long daily (Siswanto et al., 2016) and 100 years hourly precipitation and temperature time series between 1866 and 1980 (929182 hourly records in total with 10% missing values, see Figure S1 on Supplementary Material).

Hourly dew point temperature records are only available for the period 1866 – 1966 (806414 hourly records, <30% missing values including no data between 1967 and 1980). Missing values are mostly related to the years with no observational activity (15 years) due to political issues. Daily records of dew point temperature are available for the entire time period. A homogeneity check of the hourly dew point time series has been applied using the RHtestsV4 package[1]. No significant change points were found in the mean or variance of the yearly and monthly time series, besides the episodes with no-observation years. Detailed information about the data history, quality control, missing values, homogeneity procedures, and trends of temperature and precipitation datasets can be found in (Siswanto et al., 2016). The continuity check of gradual changes in temperature during the period 1991 - 1999 with neighbouring station data has been verified as documented in their Supplementary Material.

1 http://etccdi.pacificclimate.org/software.shtml

Readers are also referred to Brandsma and Jilderda (2011) and Können et al. (1998) for a historical overview of the observation site and its datasets.

For the period 2002 – 2016 atmospheric soundings collected twice per day at 00 UTC (07 LT) and 12 UTC (19 LT) at the Soekarno-Hatta Int' l Airport (SHIA) at Cengkareng (20 km distance from Jakarta). These were analysed for convective characteristics prior to three hourly accumulated rainfall events recorded at Soekarno-Hatta International Airport (SHIA), Pondok Betung, Tanjung Priok, and Kemayoran between 2014 and 2016. Standard meteorological temperature and humidity observations taken at in situ observatories in and around the greater city area of Jakarta are collected for 1985 – 2010.

Temperature and humidity are aggregated for both urban and rural environments. Urban data represent the average of measurements taken at BMKG' s meteorological stations within the Jakarta city, namely Kemayoran/BMKG headquarter (6.15°S, 106.84°E, WMO ID: 96745), Tanjung Priok harbour (6.11°S, 106.88°E, WMO ID: 96741), and Halim PK Airport (6.27°S, 100.89°E, WMO ID: 96747, ICAO ID: WIHH) indicated as location 1, 2, 3, on the map of Figure 1. Rural data is represented by the average of measurements taken at BMKG' s meteorological stations at Darmaga Bogor (6.50°S, 106.75°E, WMO ID: 96753) and Citeko (6.70°S, 106.85°E, WMO ID: 96751) indicated as location 7 and 8 on the map of Figure 1. Location 5 and 6 were not included in the analysis because they were not clearly classified as urban or rural.

Hourly precipitation data was mainly digitized from pluviograph paper strip charts of the 19th and 20th century, with a rainfall interval of 0.1 millimetres. In the analysis, we defined an hourly rainfall event with a threshold of 0.2 millimetre per hour (Manton et al., 2001). Hourly rainfall under this threshold is used as a separator of different events. Hourly precipitation data are stratified into cumulative multi-hour amounts in different ways. For most analyses data are classified into rainfall duration categories for which frequency and intensity distributions are calculated. A rainfall duration class is determined by the number of consecutive hours with precipitation intensity exceeding a given threshold. For the precipitation-temperature scaling, hourly precipitation data are binned into air and dew-point temperature intervals. For each bin, the 90th, 99th, and

99.9th precipitation percentiles are computed to determine the hourly extreme precipitation.

Long-term trends of precipitation characteristics are assessed by comparing three 10-year climate periods, referring to the early 20th century (1901 – 1910), mid-century (1971 – 1980), and recent (2001 – 2010) episodes. We compare the seasonally mean diurnal cycles of rainfall and temperature for these climate periods. Long-term changes in contrasting climate characteristics between the city of Jakarta and surrounding non-urban areas are investigated using the geographic setting of rural station data depicted in Figure 1. Spatially aggregated temperature time series are constructed after correcting for station altitude differences with respect to the altitude of Jakarta Obs. station (8m a.s.l.) using a standard lapse rate of -0.65°C/100 meter. Hourly relative humidity is computed from observed hourly tempera- ture and dew point temperature. Time averaged relative humidity is calculated from hourly relative humidity data. All analyses are performed with R[2]. Fig. 1

3. Results

3.1 Short duration rainfall increases

Fig. 2

First, we present the intensity-frequency-duration relation of Jakarta sub-daily rainfall events. Figure 2 shows cumulative rainfall (intensity) and the number of events (frequency) for different duration classes (hourly bins). The analysis is performed separately for all rainfall data and extreme rainfall events exceeding the 95th-percentile. The 95th-percentile thresholds are calculated for every rainfall duration class. Results are shown for the wet (NDJFM) and dry (MJJAS) monsoon seasons in the three distinct climate episodes 1901 – 1910, 1971 – 1980, and 2001 – 2010.

For each duration class, the frequency of events shows a gradual increase over the three climate episodes (vertical bars in Figure 2). This is most pronounced for the wet season and short duration (1 – 3 hours) events, and is visible for both mean and extreme rainfall events.

2 https://www.R-project.org

Cumulative rainfall with a duration between 2 and 6 hours has increased over time in the wet season, particularly for short-duration events. This signature is also visible for extreme rainfall, although with more noise. The number of short-duration events increases in both seasons, and these events tend to become more intense. In the dry season, no significant changes in the frequency are found.

To assess a temporal trend, we compute the annual average and the distribution of precipitation amount and frequency for each duration category. We distinguish short (1 – 3 hours continuous rain), intermediate (4 – 6 hours), and long duration events (6 – 8 hours). Short duration rainfall generally consists of convective showers and is a dominant class in the trop- ics. Figure 3A indicates a significant positive change of frequency of short durations events during the wet season. An approximate doubling in the number of events is observed over the last century, which is statistically significant (*p*-value <0.01), with a rapid increase of about 25% over the period 2001 – 2010. A small frequency increase is also observed for the intermediate duration class, while longer duration events exhibit a downward frequency trend. For longer duration events the negative trend has a relatively low confidence (*p*-value <0.1) due to the small number of events in this category. In the dry season, no notable change in the frequency of each rainfall category is shown.

For the intensity, Figure 3B shows the annual distribution of monthly maximum hourly rain-fall for each duration category. Short and intermediate duration categories show a significant intensity increase by 50% (significant at *p*-value <0.01) for both seasons, while no intensity trend is observed for the longer duration events. In contrast to the event frequency, the wet and dry seasons display a similar rainfall intensity distribution. Besides a systematic trend in short duration rainfall, an apparent inter-annual to decadal variation is present in the frequency and intensity of Jakarta rainfall. This inter-annual to decadal variability is not clearly correlated to El Niño/La Niña or IOD events (Figure 3C). This is in accordance with Lestari et al. (2019) who found only a weak relation between Jakarta's extreme precipitation and ENSO characteristics, particularly during the rainy season. Observed rainfall character- istics of the wider Maritime Continent do show a correlation with ENSO (e.g., Lestari et al., 2019; Supari et al., 2018) and the Pacific Decadal Oscillation (PDO) Fig. 3

(Yanto et al., 2016).

3.2 Diurnal timing of showers

The diurnal timing of extreme rain events is highly relevant for disaster preparedness and safety. Here we present the change in the start time distribution of short duration rainfall events over the diurnal cycle (Figure 4). The start time of these short-duration rainfall events is sampled in 6-hourly diurnal time windows, and displayed in 10-year aggregates. The morning time is defined as the starting time for the rainfall falling between 07 – 12 LT, afternoon rainfall events start between 13 – 18 LT, night-time between 19 – 24 LT, and after midnight between 01 – 06 LT. Figure 4A shows that around 60% of all rainfall events occur in the wet season (NDJFM), while in the dry season (MJJAS) this is around 20%. Most of these rainfall events occur in the afternoon (3% and 1.5% of all-time windows for the wet and dry seasons, respectively). The most visible change over the period from the early 20th century to the present is a steep increase of rainfall events occurring in the night and after midnight time windows during the wet season, and a sharp decrease of afternoon rainfall events during the dry season. Night, after midnight, and morning rainfall events show a moderate increase over time.

Concerning the timing of extreme short-duration rainfall events, we use a heavy shower threshold of >10 mm hour^{-1} (Kahlig, 1993; also used by USGS[3]). Figure 4B shows that heavy shower events increase in each time window and in both seasons over the 1901-2010 time period, although with varying rates. Again, night-time heavy shower events exhibit a steeper increase for both seasons, and stronger increases are found for all heavy shower events in the wet season. These heavy shower events account for 6% of all rainfall events, and many of them (~50%) occur during the wet season. Fig. 4

3.3 Changes in urban environment in relation to extreme precipitation

a. Urban surface warming and drying as temperature rises

3 https://water.usgs.gov/edu/

Rapid growth and urbanisation have introduced increasing occasions of problematic flood conditions regularly experienced by communities. Urban expansion can also contribute to changing patterns of regional temperature and humidity, on top of the global warming trend (IPCC, 2018). Figure 5A shows that annual mean relative humidity has decreased by approximately 6% (*p*-value <0.01) over the 20th century but with a considerable inter-annual and decadal variation. A significant rise of the surface temperature of about 1.6°C (*p*-value <0.01) over the same period is observed. Dew point temperature remained virtually constant during most of the 20th century. Fig. 5

To assess the potential impact of urban development on regional meteorology, the difference in surface temperature and relative humidity trends between urban and rural areas is presented in Figure 5C. Urban data represent the average of measurements taken at BMKG' s meteorological stations within the Jakarta city (Kemayoran, Tanjung Priok, and Halim PK), while rural data is represented by the average of measurements taken at BMKG' s meteo- rological stations at Darmaga and Citeko, Bogor (Figure 1). Over the past 30 years, the decreasing trend in relative humidity in the rural area is similar to the trend observed in the city of Jakarta. However, the steep temperature increase shown in the urban area is not present in the rural area where only a small non-significant positive trend is shown. This suggests an impact of the urban expansion of Jakarta on the regional warming trend.

Figure 6 displays the diurnal cycles of temperature, dew point temperature and relative humidity for the urban Jakarta environment, contrasting the 1900 – 1980 climatology with the recent decade 2000 – 2010. As noted by (Siswanto et al., 2016) the air temperature increase is largest during the early morning and smallest at midday (Figure 6A). Also significant changes in morning dew point (Figure 6B) and relative humidity (Figure 6C) are shown. The diurnal cycle of relative humidity in the recent decade shows a different signature during night-time than in the climatological period, with a maximum in the early morning just before sunrise, and a low relative humidity during the afternoon and evening. The dew point temperature exhibits only a small variation throughout the day during the recent decade, and the early morning minimum is no longer present. Fig. 6

The combination of urban surface warming and drying in Jakarta city is consistent with ear- lier findings on the thermal environment in Jakarta by (Widyasamratri et al., 2014). Their results are based on seven temperature and humidity observation sites during a field cam- paign in the 2012 transition period between dry and the pre-wet monsoon season. Higher temperatures and lower humidity were observed around noon over densely urbanised areas than over the sparsely urbanised areas. A near-surface decrease in the humidity of the urban Jakarta atmosphere can be related to a reduction of evaporation over strongly urbanized sur- faces. In addition, the elevated inner-city temperature and reduced soil moisture availability contribute to lower urban relative humidity (e.g., Blake et al., 2011).

b. Scaling of extreme precipitation with local temperature

Fig. 7

Atmospheric saturation vapor pressure increases with air temperature with 7%/°C fol- lowing the Clausius-Clapeyron (CC) relationship. Increases of precipitation intensity follow- ing a rate exceeding CC is labelled as super-CC scaling (1CC and 2CC denote the scaling of 7% and 14% per degree warming, respectively). Results of a scaling analysis of extreme hourly precipitation as a function of temperature (T) and dew point temperature (Td) are shown in Figure 7, following Lenderink and van Meijgaard (2010). After sorting all hourly precipitation events in 1°C bin intervals of T and Td, the 90th, 99th, and 99.9th -percentiles for each temperature bin are computed. Corresponding T and Td values are taken 4 hours prior to the precipitation events, to allow some time for convection to respond to environ- mental surface conditions.

Figure 7A shows the results of this analysis for air temperature. It indicates a 2CC scaling of the 90th percentile over a temperature interval ranging between 22° – 31°C. For the higher percentiles, this 2CC relation is found in a smaller temperature range (23° – 25°C), returning to a 1CC scaling at higher temperatures. The scaling relation between the dew point and the hourly rainfall extremes displays a 2CC relation until Td exceeds ∼25°C for all precipitation intensity categories. The dew point range in which 2CC applies is wider than the previous findings of Lenderink and van Meijgaard (2010), who detect 2CC scaling for a 12° – 22°C Td range for the Netherlands and Hongkong.

Observations at other locations, such as in South Korea (Park and Min, 2017), in the French Mediterranean region (Drobinski et al., 2018), and in the Alps of south-eastern Austria (Schroeer and Kirchengast, 2018), showed similar scaling behaviour with varying (dew point) temperature ranges. A more recent study by Ali et al. (2021) shows that in a global dataset over 7000 hourly precipitation gauges across six macro-regions, a consistently strong relationship between hourly precipitation extremes and dew point temperature is found at scaling rates from 1CC to 2CC at more than 60% of the gauges, peaking in the tropics at a median rate of ~1.5CC. 2CC scaling implies additional dynamical feedbacks on precipitation formation, such as large-scale dynamics, orography, and local features of atmospheric convection. Also, various physical mechanisms may be responsible for the limited extent over which 2CC applies.

Generally, the convection triggered in the (early) morning hours takes place under lower temperature conditions than afternoon convection, while moisture availability is sufficient. Intense convective precipitation needs to be fuelled by available moisture, which may be sourced from advection and evaporation from surrounding land and ocean areas. During daytime under the dry surface and high-temperature conditions, the supply of moisture may be limited (Changnon, 1979; Vogel et al., 2018).

3.4 Convective instability and extreme precipitation

Extreme rainfall in Jakarta is governed by local thermodynamics, but the presence of super-CC scaling indicates that specific atmospheric convection and dynamical processes may intensify the precipitation formation process. We analyse the atmospheric convection and its possible dynamical interactions from 930 selected atmospheric sounding data from SHIA between 2002 and 2016. The soundings are selected for favourable conditions for triggering convection in a subsequent couple of hours. For both morning (00 UTC, 07 LT) and evening (12 UTC, 19 LT) soundings the Convective Available Potential Energy (CAPE) is calculated. Higher CAPE indicates an unstable planetary boundary layer and middle troposphere, which is favourable for convection by the rapid ascent of warm air parcels, particularly when abundant moisture in the lower troposphere is available (Seeley and Romps, 2015).

The degree of convective instability and intensity of precipitation in this region is presumably dependent on the state of the Madden-Julian Oscillation MJO (Wu et al., 2013). Also, air mass advection by strong north-westerlies resulting from an emergence of northerly cold surges or CENS (Chang et al., 2005; Hattori et al., 2011; Yulihastin et al., 2019) during the peak of the Asian monsoon circulation (December to February) may play a role. However, cold surge frequency decreases when the MJO is present (Chang et al., 2005), and the MJO wind pattern tends to be opposite to the cold surge wind pattern.

In our analysis, we identify the role of MJO events on rainfall in Jakarta. For this, the Real-time Multivariate MJO (RMM) index (Wheeler and Hendon, 2004) is used, and MJO is indicated by RMM phases 3, 4, 5, or 6 over the Maritime Continent with an amplitude greater than 1 to ensure their significant appearance. We define MJO-triggered rainfall events as rainfall on a day where the rain is evenly distributed in all weather stations in Jakarta (Kemayoran, Halim PK, Tanjung Priok, Pondok Betung or SHIA) with daily rainfall exceeding at least 5 mm day^{-1}, or when daily precipitation exceeding 50 mm day^{-1} recorded in one of these stations.

Figure 8 shows the relationship between accumulated 3 hourly day and night time rainfall and preceding surface temperature, dew point, and CAPE for days with and without a strong forcing from MJO. The results confirm that in general more rainfall and higher intensity occurs in conditions with MJO forcing (Figure 8A) than without an MJO background (Figure 8B), particularly for heavy and extreme rainfall categories (≥50 and ≥100 mm 3hour^{-1}). However, its effect on sub-daily rainfall intensity is not clear (Figure S2 on Supplementary Material). In the morning hours, CAPE is generally low. Rainfall intensity is distributed in narrow ranges of temperature and dew point. During MJO events, higher values of CAPE (1000 – 2500 J kg^{-1}) are observed in the evening as temperature and dew point also show higher values, but rainfall intensity is not coherently associated with

CAPE. More intense (≥50 and ≥100 mm 3hour^{-1}) rainfall is observed at a higher temperature, dew point, and CAPE, which preferably occurs at late afternoon or evening moments. Night-time rainfall is observed within a wider temperature range 23° – 30°C (dew point temperature range 22° – 26°C), while morning rainfall occurs commonly within a somewhat smaller temperature range 23° – 27°C (dew point temperature range 22° – 25°C). During MJO events the dependence of particularly night-time CAPE on local surface (dew point) temperature is stronger. A high CAPE (1000 – 2500 J kg^{-1}) is commonly found when an MJO-dominated atmospheric background coincides with the monsoon systems in India. Strong pseudo-adiabatic buoyancy up to the upper troposphere is observed during an active monsoon period (Thomas et al., 2018).

In the subset of days without MJO forcing (Figure 8B), intense rainfalls are generally less frequent than with MJO forcing. Most rainfall events occur in a somewhat more concentrated temperature range of 23° – 29°C. Night-time rainfall occurs at higher temperatures and dew points than during day-time. High CAPE values (1000 – 2000 J kg^{-1}) occur within the 26° – 28°C temperature range in combination with high dew points. The response of precipitation to local surface temperature/dew point temperature is stronger under conditions without MJO forcing.

Fig. 8

The dependence of extreme precipitation on local surface (dew point) temperature is governed by both thermodynamic and atmospheric dynamics aspects. Night-time rainfall events occur regardless of the MJO dynamic forcing. However, intense rainfall produced from greater convective instability is more frequently observed in a dynamic atmospheric back- ground. Dong et al. (2019) pointed out that for Chinese stations in the south-eastern regions, a geographically coherent structure is found in the dependence of precipitation intensity to temperature-induced changes in available water vapor and atmospheric convection. From our observations over the Jakarta area changes in convective instability related to surface warming do not show strong signals or markable changes in the likelihood for heavy or extreme precipitation.

4. Discussion: the role of large-scale atmosphere dynamics,

urbanisation and climate change in the increase of short duration rainfall extremes

Increasing short duration rainfall extremes in a warmer climate have been widely addressed by recent research (e.g., Westra et al., 2014; Park and Min, 2017; Bürger et al., 2019; Yu et al., 2020; Fowler et al., 2021). Our observations from historical data since 1900 show a significant increase of short duration rainfall extremes in Jakarta (Figs. 2, 3, 4, and 7), a representative for tropical humid – monsoon regions. Also, we observe an enhanced surface temperature trend in the urbanized area compared to surrounding rural stations. Annual average relative humidity monotonically decreases in both urban and rural areas (Figure 5), while specific humidity and dew point increase slightly over time. We find that short-duration rainfall intensity and frequency increases particularly in the wet seasons. Jakarta is a delta city where water vapour is available abundantly from the surrounding tropical oceans. This leads to high values of the total water column and precipitation frequency.

For the Jakarta location, the increase in short-duration rainfall (extremes) during the wet season may be related to an enhanced land–ocean contrast in the response of moisture convergence (precipitation (P) – evaporation (E)) to global warming. Byrne and O’Gorman (2015) point at a larger change in P–E changes over the ocean than over land. Changes over the ocean broadly follow a thermodynamic scaling of the atmospheric moisture convergence: the so-called “wet-gets-wetter, dry-gets-drier” mechanism. This does not simply apply over the land area, where the P–E response is constrained by limited moisture availability. Changes in atmospheric circulation can overrule local precipitation statistics, and modify horizontal gradients of temperature and fractional changes in relative humidity over land. During the wet season, a dominant north–westerly Asian monsoon transports abundant moisture evaporated from the sea towards the coastal city of Jakarta, which favours heavy precipitation.

Our analysis shows that short duration rainfall events have a preference to occur in the night to morning hours, and its frequency increases significantly in more recent decades in Jakarta.

However, early morning rainfall is also observed to increase in the wet season. Excessive rainfall in the city center or near the coast that occurs in the early morning time (Yulihastin et al., 2019; Nuryanto et al., 2019) led to big flooding events in 2013, 2014, 2015 (Siswanto et al., 2015, 2016, 2017), and latest in 2020. During 1992 – 1999 Boundary Layer Radar data analysed by (Renggono et al., 2001) showed a small shift from stratiform to deep convective precipitation during December to February between 03 LT and 06 LT at Serpong, 37 km southwest off Kemayoran Jakarta. In the Maritime Continent, the typical afternoon precipitation peaks over land are complemented with convective morning precipitation peaks which are governed by the ocean (Mori et al., 2004; Qian, 2008; Yamanaka et al., 2018). This is driven by sea-land breezes interaction with the prevailing background monsoon flows (Hadi et al., 2002; Araki et al., 2006).

The urbanisation of the greater Jakarta area has likely contributed to the increase in surface temperature (Figure 5) and subsequently to an increase in CAPE. Modelling studies confirm high CAPE values in the presence of high near-surface temperatures (Rasmussen et al., 2017; Meredith et al., 2019). However, additional (dynamical) processes other than CAPE affect convection and rainfall formation. A modelling study by Kanda et al. (2001) showed that urbanisation affected the intensity and position of a local cumulus cloud formation in the Tokyo metropolitan area through enhancement of local upward motions and changes in the near-surface horizontal pressure gradient between urban and suburban areas. The urban heat and dry island may deform or change the behaviour of sea-breeze circulation (Martilli, 2003; Tokairin et al., 2010).

Low-level moisture convergence and wind convergence anomalies tend to be larger over a drier (warmer) surface and can lead to precipitation anomalies, as demonstrated in a low- resolution general circulation model (GCM) with an idealized continent situated on the equator (Cook, 1994). At the latitude of the intertropical convergence zone (ITCZ), dry convection drives anomalous low level convergence, which is larger over a drier (warmer) surface. In the case of Jakarta, similar warm surface conditions in the city may generate mesoscale convective systems during night-time (Mori et al., 2018), leading to intense rainfall events.

The warmer city surface may also interact with converging local circulations (land-sea breeze), and further promote the repeated development of convective systems that generate rainfall in the early morning (Siswanto et al., 2016). A modelling study on impacts of land-use changes on local meteorological conditions in the Jakarta area by (Tokairin et al., 2010) revealed that in the present-day land-use scenario over Jakarta the sea breeze develops at an earlier moment in the diurnal cycle than for historic land use conditions, caused by heat advection from the new urban areas in South Jakarta into the old city (Central Jakarta). To investigate the complex combination of mechanisms leading to heavy precipitation in the Jakarta area additional analyses are required, for instance by regional modelling work where different urbanisation scenarios are included to explore its impact on the development of extreme precipitation. This modelling set-up would require substantial tuning of the experimental design and computing resources, and is out of scope for the present study.

Our analysis indicates that both local factors and the large-scale dynamics background contribute to the rainfall characteristics. Local extreme rainfall – temperature scaling is stronger when the large-scale atmospheric forcing is smaller. This is consistent with the finding of (Magan et al., 2020) for the rainfall – temperature sensitivity (scaling) in tropical Australia, who demonstrated this scaling to vary with weather types. Wet monsoon weather types result in 1CC scaling, while dry weather types (with small remote advection) produce up to twice a 1CC scaling. The increase of convective precipitation extremes with surface warming is also governed by the stratification of the overlying atmosphere. Super Clausius – Clapeyron scaling has been found in model experiments where the surface warming was extended uni- formly with height, which reduces the static stability of a moist atmosphere leading to faster updrafts (Attema et al., 2014). Exploring the mechanisms of climate change induced convective activity in the midlatitudes, strong increases of CAPE in climate change model simulations were found to be associated with near-uniform vertical temperature changes (Byrne and O' Gorman, 2015).

Observed increases of available moisture in Jakarta (particularly in the early morning), together with convergence processes of the local circulation or moisture advection from large- scale atmospheric circulation features, promote the repeated development of large convective systems that lead to intensification of morning precipitation and the rainfall peak shifting from afternoon to night-time. Meredith et al. (2019) showed that future intensification of intense rainfall events has a strong diurnal signal, with the mid-morning period displaying the largest intensification. This leads to a shift of the diurnal convective precipitation maximum from late afternoon to the overnight/morning period under a strong climate change scenario.

5. Summary and Conclusions

Using a Jakarta data record with a length exceeding 100 years, characteristics of sub-daily precipitation extremes are analysed in conjunction with temperature and relative humidity readings. A significant frequency increase of about 25% in short duration (1 – 3 hours) rainfall events was observed in 2001 – 2010 compared to the start of the 20th century, and the cumulative rainfall amount related to these events has increased by 50%. The most intense rainfall events are getting shorter in duration. Apart from a change in duration and intensity of events, a shift in the diurnal timing of the events from the afternoon to later in the night and into the early morning is observed.

Changes of the surface environment of urban Jakarta throughout the last century probably contributed to increases in CAPE. Surface warming in the urbanised city together with additional moisture availability resulting from large-scale atmospheric features in the lower atmosphere may result in warmer and more unstable air aloft, in particular in the mid-troposphere, implying a larger buoyancy into the mid-troposphere and larger and higher convective up- drafts. A direct impact of urbanisation on rainfall characteristics is not demonstrated by our observational analysis and could be explored in numerical simulation experiments.

For a subset of our data intense precipitation was found to increase with temperature at a rate approximating twice the Clausius Clapeyron (2CC) scaling, constrained to a limited temperature regime and high precipitation intensity thresholds. Increased atmospheric moisture in the early morning may promote 2CC temperature scaling triggering strong morning rainfall events, while 1CC temperature scaling is found for less extreme rainfall events. Increased extreme rainfall intensity during the night and morning time (when the air is still humid) is in agreement with the hypothetical precipitation response to considerably warmer and moister climate conditions than the present day. Given the location of Jakarta as a delta city, the abundant moisture evaporated from the sea is a continuous source of low-level moisture convergence that may develop into intense convection resulting in heavy precipitation. The study highlights the need for an appropriate and well-maintained sub-daily rainfall database which gives the opportunity to accurately monitor the impact of a changing climate on floods in urban areas.

Supplement

Supplement for this article consist of two figures, Figure S1 and Figure S2. Figure S1 (Left panel) shows the missing value and present hourly data for temperatures, dew point and precipitation at Jakarta Observatory during 1866 – 1980. (Right panel) Example of homogeneity check for the 1866 – 1966 dew point time series using RHVtest4 (see text for explanation). Figure S2 shows the relation between Jakarta rainfall and MJO phases. Step grey line chart indicates the frequency of the day when the rainfall is at least 5 mm day^{-1} is evenly distributed in all weather stations within the urban Jakarta area (Kemayoran, Halim PK, Tanjung Priok, Pondok Betung, or SHIA), or when daily precipitation exceeding 50 mm day^{-1} recorded in one of these stations. Only MJO events with an amplitude greater than 1 were selected. Boxplots indicate the sub-daily rainfall intensity that occurred in Jakarta corresponding to each MJO phase. The colored star at the end of the data series outside the boxplot for each sub-daily rainfall shows an outlier, which is the highest value of the entire data series. In terms of extreme events, this value can be identified as extreme rainfall with an extraordinary intensity far from its normal range.

Acknowledgements

This study was supported by the Joint Cooperation Program between KNMI (the Netherlands), BMKG (Indonesia), PusAir (Indonesia), and Deltares (the Netherlands). We would like to thank Mr. Agie Wandala (Center for Meteorology, BMKG) and the Meteorological Station of Soekarno-Hatta International Airport for providing the upper air data used in this study.

References

Ali, H., H. J. Fowler, G. Lenderink, E. Lewis, and D. Pritchard, 2021: Consistent large-scale response of hourly extreme precipitation to temperature variation over land. *Geophysical Research Letters*, **48(4)**, e2020GL090317. e2020GL090317 2020GL090317.

Araki, R., M. D. Yamanaka, F. Murata, H. Hashiguchi, Y. O. T. Sribimawati, M. Kudsy, and F. Renggono, 2006: Seasonal and interannual variations of diurnal cycles of wind and cloud activity observed at Serpong, West Jawa, Indonesia. *Journal of the Meteorological Society of Japan. Ser. II*, **84A**, 171 – 194.

Attema, J. J., J. M. Loriaux, and G. Lenderink, 2014: Extreme precipitation response to climate perturbations in an atmospheric mesoscale model. *Environmental Research Letters*, **9(1)**, 014003.

Barbero, R., H. J. Fowler, S. Blenkinsop, S. Westra, V. Moron, E. Lewis, S. Chan, G. Lenderink, E. Kendon, S. Guerreiro, X.-F. Li, R. Villalobos, H. Ali, and V. Mishra, 2019: A synthesis of hourly and daily precipitation extremes in different climatic regions. *Weather and Climate Extremes*, **26**, 100219.

Berg, P., C. Moseley, and J. O. Haerter, 2013: Strong increase in convective precipitation in response to higher temperatures. *Nature Geosci*, **6(3)**, 181 – 185.

Blake, R., A. Grimm, T. Ichinose, R. Horton, S. Gaffin, S. Jiong, D. Bader, and L. D. Cecil, 2011: *Urban climate: Processes, trends, and projections. Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press., Cambridge, UK, 43–81. C. Rosenzweig, W. D. Solecki, S. A. Hammer, S. Mehrotra (eds.).

Brandsma, T., and R. Jilderda, 2011: , CS8: Times series information. Final report, KNMI, https://www.knmi.nl/kennis-en-datacentrum/publicatie/cs8-times-series-information-final-report.

Bürger, G., A. Pfister, and A. Bronstert, 2019: Temperature-driven rise in extreme sub-hourly rainfall. *Journal of Climate*, **32(22)**, 7597 – 7609.

Byrne, M. P., and P. A. O' Gorman, 2015: The response of precipitation minus evapotranspiration to climate warming: Why the "wet-get-wetter, dry-get-drier" scaling does not hold over land. *Journal of Climate*, **28(20)**, 8078 – 8092.

Chang, C.-P., P. A. Harr, and H.-J. Chen, 2005: Synoptic disturbances over the Equatorial South China Sea and Western Maritime Continent during boreal winter. *Monthly Weather Review*, **133(3)**, 489 – 503.

Changnon, S., 1979: *Metropolitan Meteorological Experiment: METROMEX*. American Meteorological Society.

Cook, K. H., 1994: Mechanisms by which surface drying perturbs tropical precipitation fields. *Journal of Climate*, **7(3)**, 400–413.

Dong, W., Y. Lin, J. S. Wright, X. Y. Yuanyu Xie, and J. Guo, 2019: Precipitable water and CAPE dependence of rainfall intensities in China. *Climate Dynamics*, **52(3)**, 3357–3368.

Drobinski, P., N. D. Silva, G. Panthou, S. Bastin, C. Muller, B. Ahrens, M. Borga, D. Conte, G. Fosser, F. Giorgi, I. Güttler, V. Kotroni, L. Li, E. Morin, B. Önol, P. Quintana-Segui, R. Romera, and C. Z. Torma, 2018: Scaling precipitation extremes with temperature in the Mediterranean: past climate assessment and projection in anthropogenic scenarios. *Climate Dynamics*, **51(3)**, 1237 – 1257.

Fowler, H. J., G. Lenderink, A. F. Prein, S. Westra, R. P. Allan, N. Ban, R. Barbero, P. Berg, S. Blenkinsop, H. X. Do, S. Guerreiro, J. O. Haerter, E. J. Kendon, E. Lewis, C. Schaer, A. Sharma, G. Villarini, C. Wasko, and X. Zhang, 2021: Anthropogenic intensification of short-duration rainfall extremes. *Nature Reviews Earth & Environment*, **2(2)**, 107 – 122.

Hadi, T. W., T. Horinouchi, T. Tsuda, H. Hashiguchi, and S. Fukao, 2002: Sea-breeze circulation over Jakarta, Indonesia: A climatology based on boundary layer radar observations. *Monthly Weather Review*, **130(9)**, 2153 – 2166.

Haerter, J. O., and P. Berg, 2009: Unexpected rise in extreme precipitation caused by a shift in rain type? *Nature Geosci*, **2(6)**, 372 – 373.

Hardwick Jones, R., S. Westra, and A. Sharma, 2010: Observed relationships between extreme sub-daily precipitation, surface temperature, and relative humidity. *Geophysical Research Letters*, **37(22)**, n/a – n/a. L22805.

Hattori, M., S. Mori, and J. Matsumoto, 2011: The Cross-Equatorial Northerly Surge over the Maritime Continent and its relationship to precipitation patterns. *Journal of the Meteorological Society of Japan. Ser. II*, **89A**, 27 – 47.

Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *Journal of Climate*, **19(21)**, 5686 – 5699.

IPCC, 2013: *Summary for Policymakers in Climate Change 2013 : The Physical Science Basis*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. IPCC WG I: Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.).

IPCC, 2018: *Impacts of 1.5℃ Global Warming on Natural and Human Systems: In: Global Warming of 1.5℃. An IPCC Special Report on the impacts of global warming* *of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Cambridge University Press. In Press. IPCC WG I: Masson-Delmotte, V., P. Zhai, H.-O. Prtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. P, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.).

IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. In Press. IPCC WG I: Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Pn, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M.Huang, K.Leitzell, E.Lonnoy, J.B.R. Matt R. Yu, and B. Zhou (eds.).

Kahlig, P., 1993: On deterministic criteria for heavy rainfall at a point. *Theoretical and Applied Climatology*, **46(4)**, 203–208.

Kanda, M., Y. Inoue, and I. Uno, 2001: Numerical study on cloud lines over an urban street in Tokyo. *Boundary-Layer Meteorology*, **98(2)**, 251–273.

Können, G. P., P. D. Jones, M. H. Kaltofen, and R. J. Allan, 1998: Pre-1866 extensions of the Southern Oscillation Index using early Indonesian and Tahitian meteorological readings. *Journal of Climate*, **11(9)**, 2325–2339.

Koseki, S., T.-Y. Koh, and C.-K. Teo, 2013: Effects of the cold tongue in the south china sea on the monsoon, diurnal cycle and rainfall in the maritime continent. *Quarterly Journal of the Royal Meteorological Society*, **139(675)**, 1566–1582.

Lambert, F. H., A. R. Stine, N. Y. Krakauer, and J. C. H. Chiang, 2008: How much will precipitation increase with global warming? *EOS, Transactions American*

Geophysical Union, **89(21)**, 193 – 194.

Lau, W. K. M., K.-M. Kim, and L. Ruby Leung, 2017: Changing circulation structure and precipitation characteristics in asian monsoon regions: greenhouse warming vs. aerosol effects. *Geoscience Letters*, **4(1)**, 28.

Lenderink, G., and E. van Meijgaard, 2008: Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience*, **1**, 511 – 514.

Lenderink, G., and E. van Meijgaard, 2010: Linking increases in hourly precipitation extremes to atmospheric temperature and moisture changes. *Environmental Research Letters*, **5**, 025208.

Lenderink, G., H. Y. Mok, T. C. Lee, and G. J. van Oldenborgh, 2011: Scaling and trends of hourly precipitation extremes in two different climate zones : Hong Kong and the Netherlands. *Hydrol. Earth Syst. Sci. Discuss.*, **8**, 4701 – 4719. doi:10.5194/hessd-8-4701-2011.

Lestari, S., A. King, C. Vincent, D. Karoly, and A. Protat, 2019: Seasonal dependence of rainfall extremes in and around Jakarta, Indonesia. *Weather and Climate Extremes*, **24**, 100202.

Lutsko, N. J., and T. W. Cronin, 2018: Increase in precipitation efficiency with surface warming in radiative-convective equilibrium. *Journal of Advances in Modeling Earth Systems*, **10(11)**, 2992 – 3010.

Magan, B., S. Kim, C. Wasko, R. Barbero, V. Moron, R. Nathan, and A. Sharma, 2020: Impact of atmospheric circulation on the rainfall-temperature relationship in Australia. *Environmental Research Letters*, **15(9)**, 094098.

Manton, M., P. Della-Marta, M. Haylock, K. Hennessy, N. Nicholls, L. Chambers, D. Collins, G. Daw, A. Finet, D. Gunawan, K. Inape, H. Isobe, T. Kestin, P. Lefale, C. Leyu, T. Lwin, L. Maitrepierre, N. Ouprasitwong, C. Page, J. Pahalad, N. Plummer, M. Salinger, R. Suppiah, V. Tran, B. Trewin, I. Tibig, and D. Yee, 2001: Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961 – 1998. *International Journal of Climatology*, **21(3)**, 269 – 284.

Martilli, A., 2003: A two-dimensional numerical study of the impact of a city on atmospheric circulation and pollutant dispersion in a coastal environment. *Boundary-Layer Meteorology*, **108(1)**, 91 – 119.

McCarthy, M. P., M. J. Best, and R. A. Betts, 2010: Climate change in cities due to global warming and urban effects. *Geophysical Research Letters*, **37(9)**, n/a – n/a. L09705.

Meehl, G. A., C. Tebaldi, H. Teng, and T. C. Peterson, 2007: Current and future U.S. weather extremes and El Ni*Geophysical Research Letters*, **34(20)**, n/a – n/a. L20704.

Meredith, E. P., U. Ulbrich, and H. W. Rust, 2019: The diurnal nature of future extreme precipitation intensification. *Geophysical Research Letters*, **46(13)**, 7680 – 7689.

Miao, C., Q. Sun, A. G. L. Borthwick, and Q. Duan, 2016: Linkage between hourly precipitation events and atmospheric temperature changes over China during the warm season. *Scientific Reports*, **6**, 22543 EP.

Mori, S., J.-I. Hamada, M. Hattori, P.-M. Wu, M. Katsumata, N. Endo, K. Ichiyanagi, H. Hashiguchi, A. A. Arbain, R. Sulistyowati, S. Lestari, F. Syamsudin, T. Manik, and M. D. Yamanaka, 2018: Meridional march of diurnal rainfall over jakarta, indonesia, observed with a c-band doppler radar: an overview of the harimau2010 campaign. *Progress in Earth and Planetary Science*, **5(1)**, 47.

Mori, S., H. Jun-Ichi, Y. I. Tauhid, M. D. Yamanaka, N. Okamoto, F. Murata, N. Sakurai, H. Hashiguchi, and T. Sribimawati, 2004: Diurnal land – sea rainfall peak migration over Sumatera island, Indonesian Maritime Continent, observed by TRMM Satellite and intensive rawinsonde soundings. *Monthly Weather Review*, **132(8)**, 2021 – 2039.

Muller, C., and Y. Takayabu, 2020: Response of precipitation extremes to warming: what have we learned from theory and idealized cloud-resolving simulations, and what remains to be learned? *Environmental Research Letters*, **15(3)**, 035001.

Nuryanto, D. E., H. Pawitan, R. Hidayat, and E. Aldrian, 2019: Characteristics of two mesoscale convective systems (MCSs) over the Greater Jakarta: case of heavy rainfall period 15 – 18 January 2013. *Geoscience Letters*, **6(1)**, 1.

O'Gorman, P. A., 2015: Precipitation extremes under climate change. *Current Climate Change Reports*, **1(2)**, 49 – 59.

Park, I.-H., and S.-K. Min, 2017: Role of convective precipitation in the relationship between subdaily extreme precipitation and temperature. *Journal of Climate*, **30(23)**, 9527 – 9537.

Qian, J.-H., 2008: Why precipitation is mostly concentrated over islands in the Maritime Continent. *Journal of the Atmospheric Sciences*, **65**, 1428 – 1441. doi: 10.1175/2007JAS2422.1.

Rasmussen, K. L., A. F. Prein, R. M. Rasmussen, K. Ikeda, and C. Liu, 2017: Changes in the convective population and thermodynamic environments in convection-permitting regional climate simulations over the United States. *Climate Dynamics*.

Renggono, F., H. Hashiguchi, S. Fukao, M. D. Yamanaka, S.-Y. Ogino, N. Okamoto, F. Murata, B. P. Sitorus, M. Kudsy, M. Kartasasmita, and G. Ibrahim, 2001: Precipitating clouds observed by 1.3-ghz boundary layer radars in equatorial Indonesia. *Annales Geophysicae*, **19(8)**, 889 – 897.

Schroeer, K., and G. Kirchengast, 2018: Sensitivity of extreme precipitation to temperature: the variability of scaling factors from a regional to local perspective. *Climate Dynamics*, **50(11)**, 3981 – 3994.

Seeley, J. T., and D. M. Romps, 2015: Why does tropical convective available potential energy (CAPE) increase with warming? *Geophysical Research Letters*, **42(23)**, 10,429 – 10,437. 2015GL066199.

Shaw, S. B., A. A. Royem, and S. J. Riha, 2011: The relationship between extreme hourly precipitation and surface temperature in different hydroclimatic regions of the united states. *Journal of Hydrometeorology*, **12(2)**, 319 – 325.

Siswanto, G. van der Schrier, G. J. van Oldenborgh, B. van den Hurk, E. Aldrian, Y. Swarinoto, W. Sulistya, and A. E. Sakya, 2017: A very unusual precipitation event associated with the 2015 floods in Jakarta: an analysis of the meteorological factors. *Weather and Climate Extremes*, **16**, 23 – 28.

Siswanto, S., G. J. van Oldenborgh, G. van der Schrier, R. Jilderda, and B. van den Hurk, 2016: Temperature, extreme precipitation, and diurnal rainfall changes in the urbanized Jakarta city during the past 130 years. *International Journal of Climatology*, **36**, 3207 – 3225. http://dx.doi.org/10.1002/joc.4548.

Siswanto, S., G. J. van Oldenborgh, G. van der Schrier, G. Lenderink, and B. van den Hurk, 2015: Trends in high-daily precipitation events in Jakarta and the flooding of January 2014. *Bull. Amer. Meteor. Soc*, **96**, S131 – S135.

Supari, F. Tangang, L. Juneng, and E. Aldrian, 2017: Observed changes in extreme temperature and precipitation over Indonesia. *International Journal of Climatology*, **37(4)**, 1979 – 1997.

Supari, F. Tangang, E. Salimun, E. Aldrian, A. Sopaheluwakan, and L. Juneng, 2018: Enso modulation of seasonal rainfall and extremes in indonesia. *Climate Dynamics*, **51(7)**, 2559 – 2580.

Thomas, L., N. Malap, W. W. Grabowski, K. Dani, and T. V. Prabha, 2018: Convective environment in pre-monsoon and monsoon conditions over the Indian subcontinent: the impact of surface forcing. *Atmospheric Chemistry and Physics*, **18(10)**, 7473 – 7488.

Tokairin, T., A. Sofyan, and T. Kitada, 2010: Effect of land use changes on local meteorological conditions in Jakarta, Indonesia: toward the evaluation of the thermal environment of megacities in Asia. *International Journal of Climatology*, **30(13)**, 1931 – 1941.

Trenberth, K. E., 2011: Changes in precipitation with climate change. *Climate Research*, **47(4)**, 123 – 138.

Utsumi, N., S. Seto, S. Kanae, E. E. Maeda, and T. Oki, 2011: Does higher surface temperature intensify extreme precipitation? *Geophysical Research Letters*, **38(16)**, n/a – n/a. L16708.

Vogel, M. M., J. Zscheischler, and S. I. Seneviratne, 2018: Varying soil moisture – atmosphere feedbacks explain divergent temperature extremes and precipitation projections in central Europe. *Earth System Dynamics*, **9(3)**, 1107 – 1125.

Wentz, F. J., L. Ricciardulli, K. Hilburn, and C. Mears, 2007: How much more rain will global warming bring? *Science*, **317(5835)**, 233 – 235.

Westra, S., H. J. Fowler, J. P. Evans, L. V. Alexander, P. Berg, F. Johnson, E. J. Kendon, G. Lenderink, and N. M. Roberts, 2014: Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics*, **52(3)**, 522 – 555. 2014RG000464.

Wheeler, M. C., and H. H. Hendon, 2004: An all-season real-time multivariate mjo index: Development of an index for monitoring and prediction. *Monthly Weather Review*, **132(8)**, 1917 – 1932.

Widyasamratri, H., K. Souma, T. Suetsugi, H. Ishidaira, Y. Ichikawa, H. Kobayashi, I. Inagaki, and K. Kakizawa, 2014: Heat and dry islands observed over jakarta, indonesia, in 2012. *Proceedings of the International Association of Hydrological Sciences*, **364**, 140 – 144.

Wu, M., H. Lam, and K. Li, 2013: Characterization and indexing of heavy rainstorms in hong kong. *Meteorological Applications* n/a.

Yamanaka, M. D., S.-Y. Ogino, P.-M. Wu, H. Jun-Ichi, S. Mori, J. Matsumoto, and F. Syamsudin, 2018: Maritime continent coastlines controlling Earth’ s climate. *Progress in Earth and Planetary Science*, **5(1)**, 21.

Yanto, B. Rajagopalan, and E. Zagona, 2016: Space – time variability of Indonesian rainfall at inter-annual and multi-decadal time scales. *Climate Dynamics*, **47(9)**, 2975 – 2989.

Yu, L., S. Zhong, Y. Qiu, and X. Liang, 2020: Trend in short-duration extreme precipitation in Hong Kong. *Frontiers in Environmental Science*, **8**, 164.

Yulihastin, E., T. W. Hadi, and N. S. Ningsih, 2019: Diurnal rainfall propagation relate to cold surge-cold tongue interaction over the northern coast of West Java. *IOP Conference Series: Earth and Environmental Science*, **303**.

List of Figures

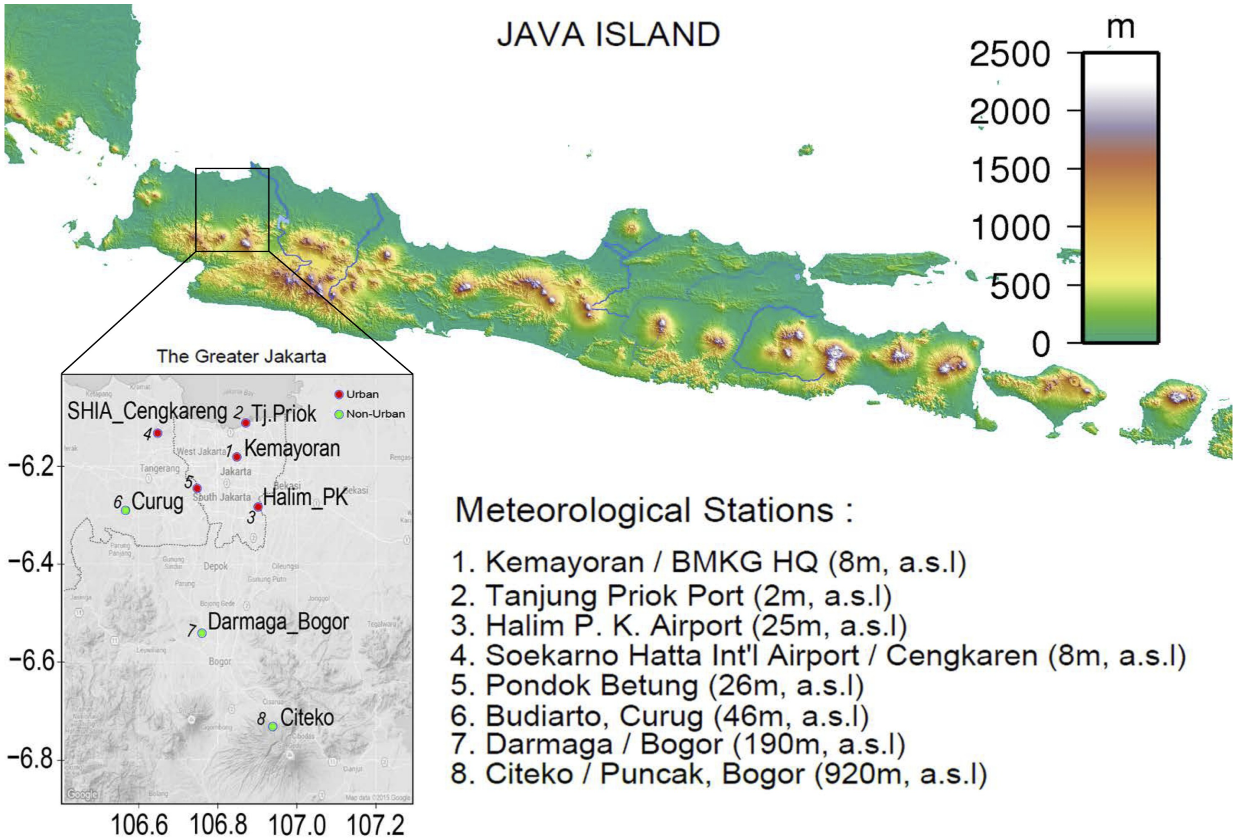

Fig. 1. The Greater Jakarta map in the setting of the Java Island topographical map. The Greater Jakarta, or the Jakarta metropolitan area (in the inset), known locally as Jabodetabekpunjur (an acronym of Jakarta – Bogor – Depok – Tangerang – Bekasi – Puncak – Cianjur), is the most populous metropolitan area in Indonesia. The area is crossed by a network of 13 rivers, flowing from mountainous and hilly areas in the Bogor and Cianjur regions to Jakarta through the alluvial and coastal lowlands of North Jakarta. BMKG operates eight meteorological stations which are classified as urban (red dot) and rural (green dot) in this study.

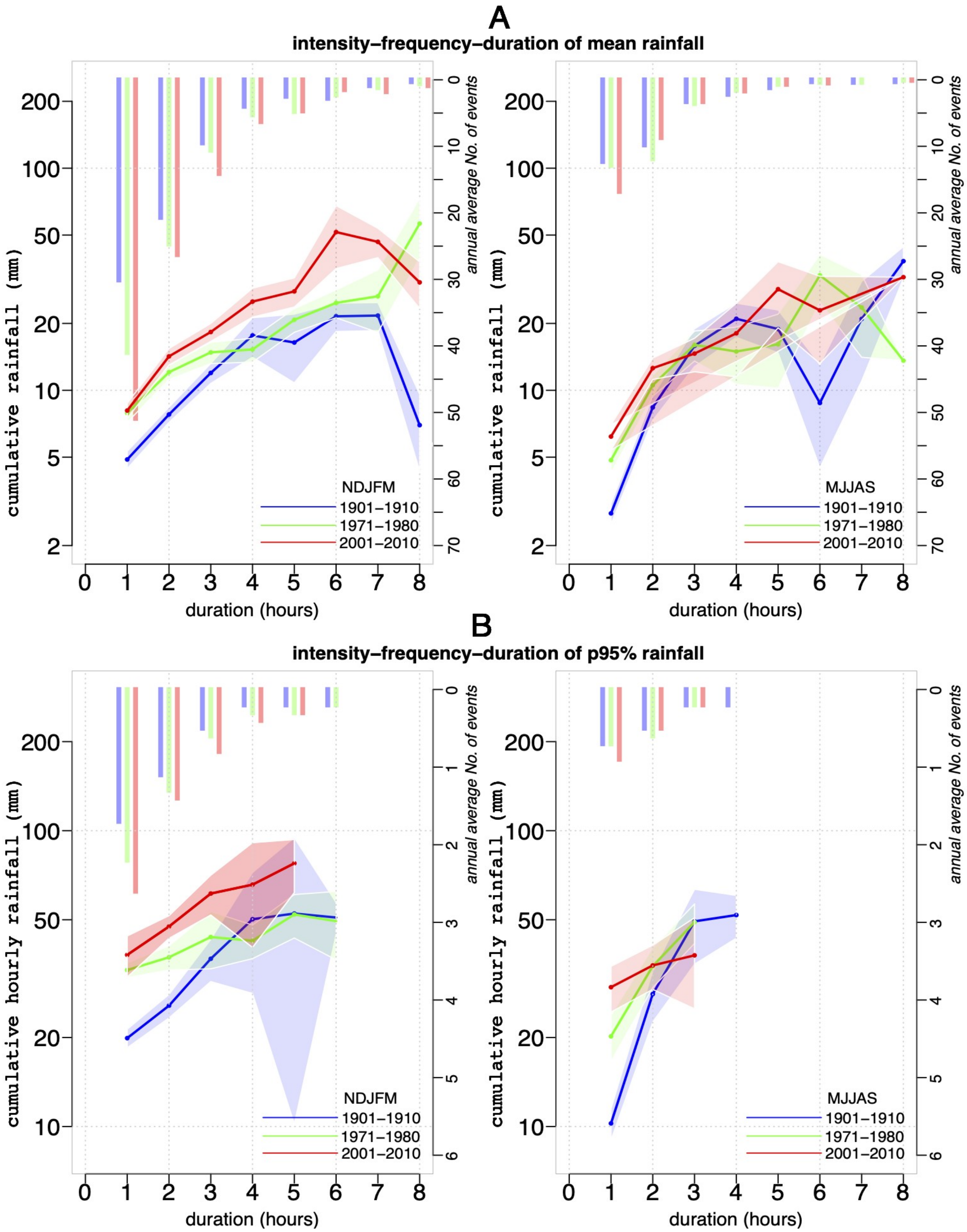

Fig. 2. Precipitation intensity-frequency-duration relation of (A) mean of all rainfall events and (B) extreme precipitation for (left) wet and (right) dry monsoon regimes for three different climate periods (coloured lines). A rainfall event is defined as the occurrence of hourly rainfall ≥0.2 mm, and extreme rainfall is represented by the class of cumulative hourly rainfall exceeding the 95th-percentile threshold for each duration class. Shading for the climate periods indicates the standard errors of the means per rainfall duration class. Vertical bars (labelled at right axis) indicate the total number of wet events. Single events in a given rainfall duration class are not displayed.

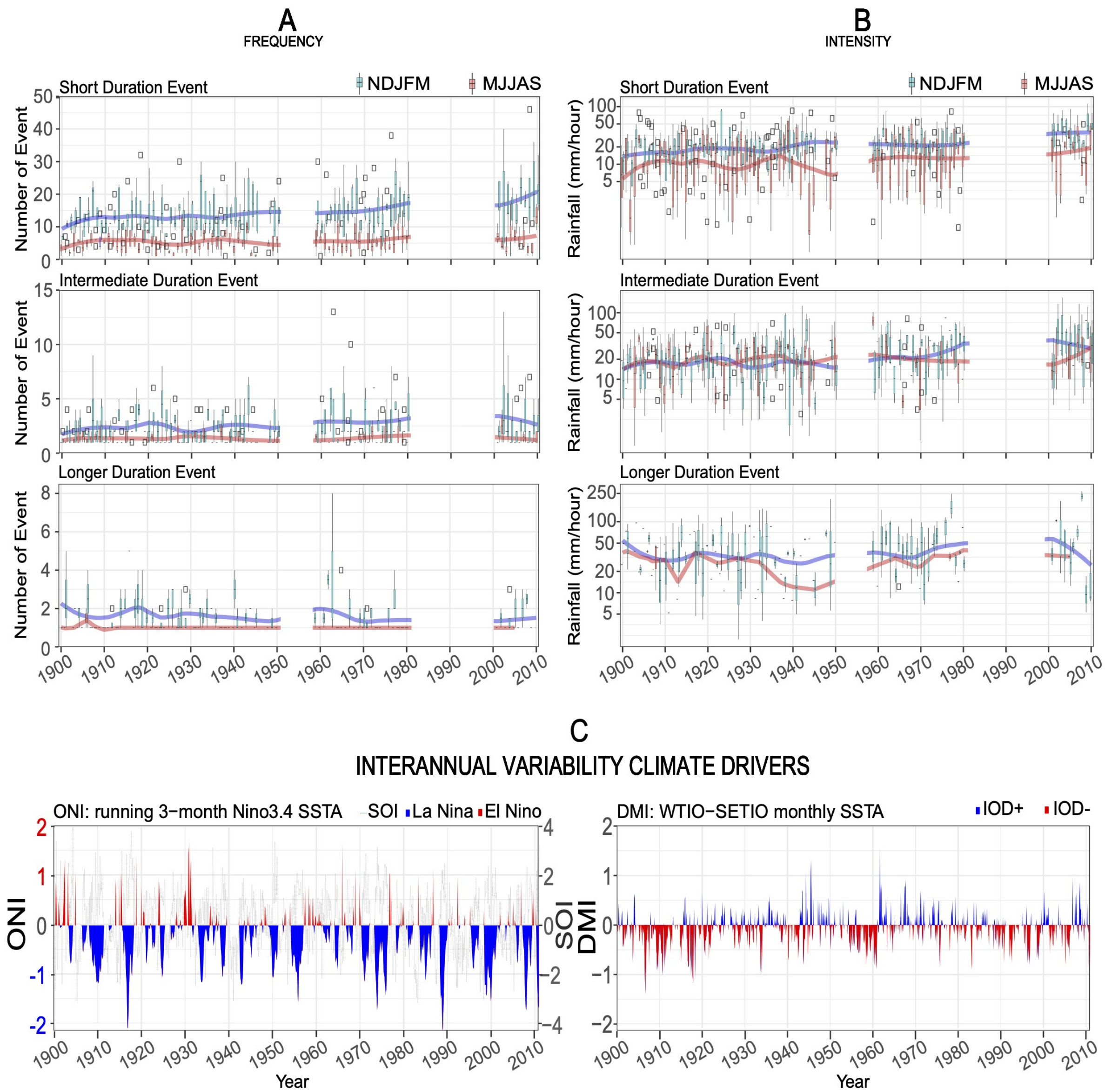

Fig. 3. Annual frequency (A, left panels) and intensity (B, right panels) of short (1 – 3 hours; top), intermediate (4 – 6 hours; middle), and long rainfall events (>6 hours; bottom) for the wet season (NDJFM, blue lines/symbols) and dry season (MJJAS, red lines/symbols). The boxplot of the annual variability of monthly maximum rainfall represents the Inter Quartile Range (IQR), with the median shown as a horizontal line within the box. Vertical dashed lines indicate the extent of 1.5 times the IQR. Blue (red) thick lines represent low-pass-filtered annual NDJFM (MJJAS) series using the Loess smoother, with span parameter=3/10 (compatible with 3-years moving average). Round dots represent individual outliers. Panel C shows the inter-annual variability of the Oceanic Niño Index (ONI) and Southern Oscillation Index (SOI) to indicate ENSO (El Niño (red) and La Niña (blue) events), and the Dipole Mode Index (DMI) to indicate IOD events.

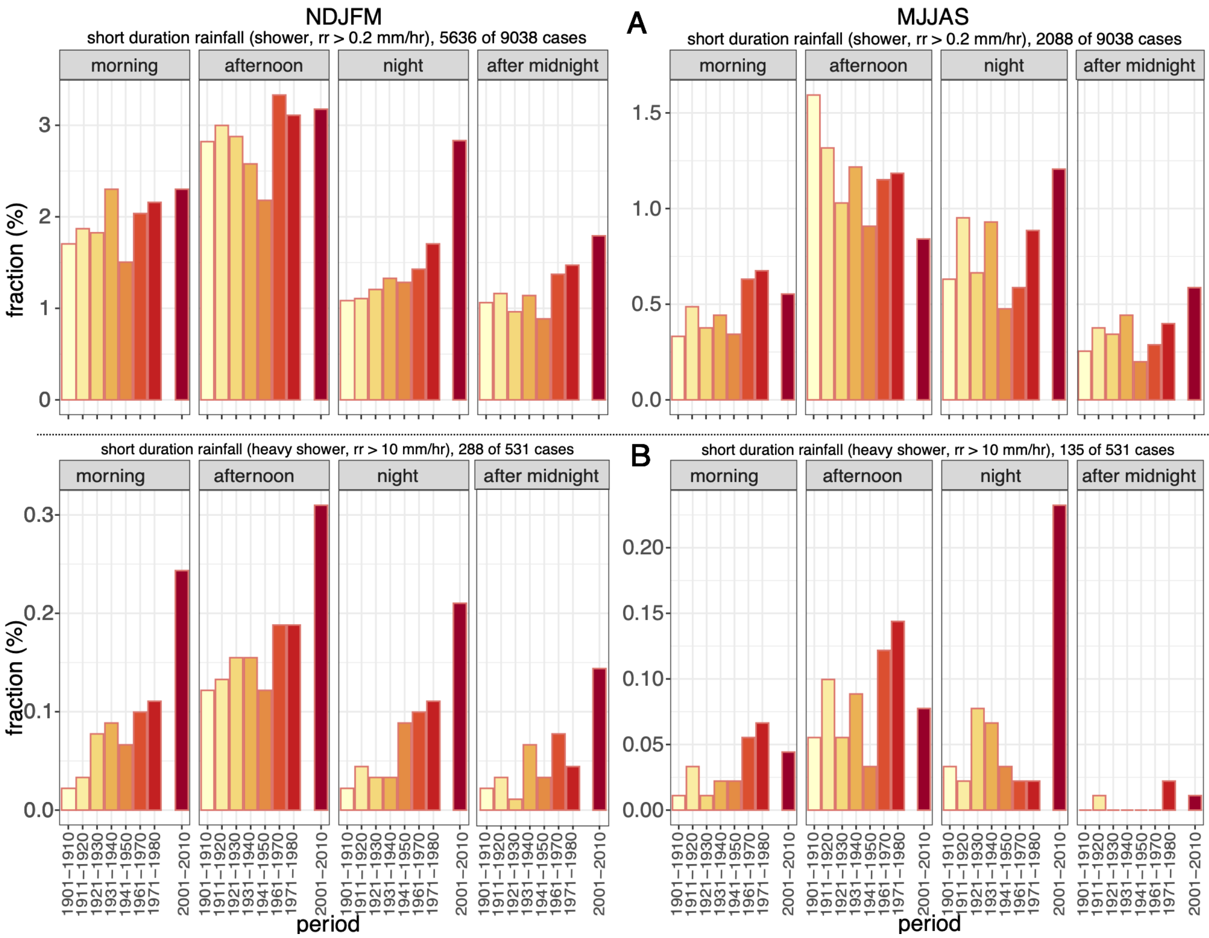

Fig. 4. (A) Fraction of short duration rainfall events in diurnal time windows for each 10-year period from 1901 to 1980, and 2001 to 2010. Diurnal time windows are indicated by "morning" (rainfall starting hour between 07 and 12 local time (LT)), "afternoon" (13 – 18 LT), "night" (19 – 24 LT), and "after midnight" (01 – 06 LT), and are labelled separately for wet (NDJFM) and dry (MJJAS) seasons. (B) same as A, but valid for short duration rainfall in the category heavy shower (hourly rainfall >10 mm). Note that there is a period gap between the period 1971 – 1980 and 2001 – 2010.

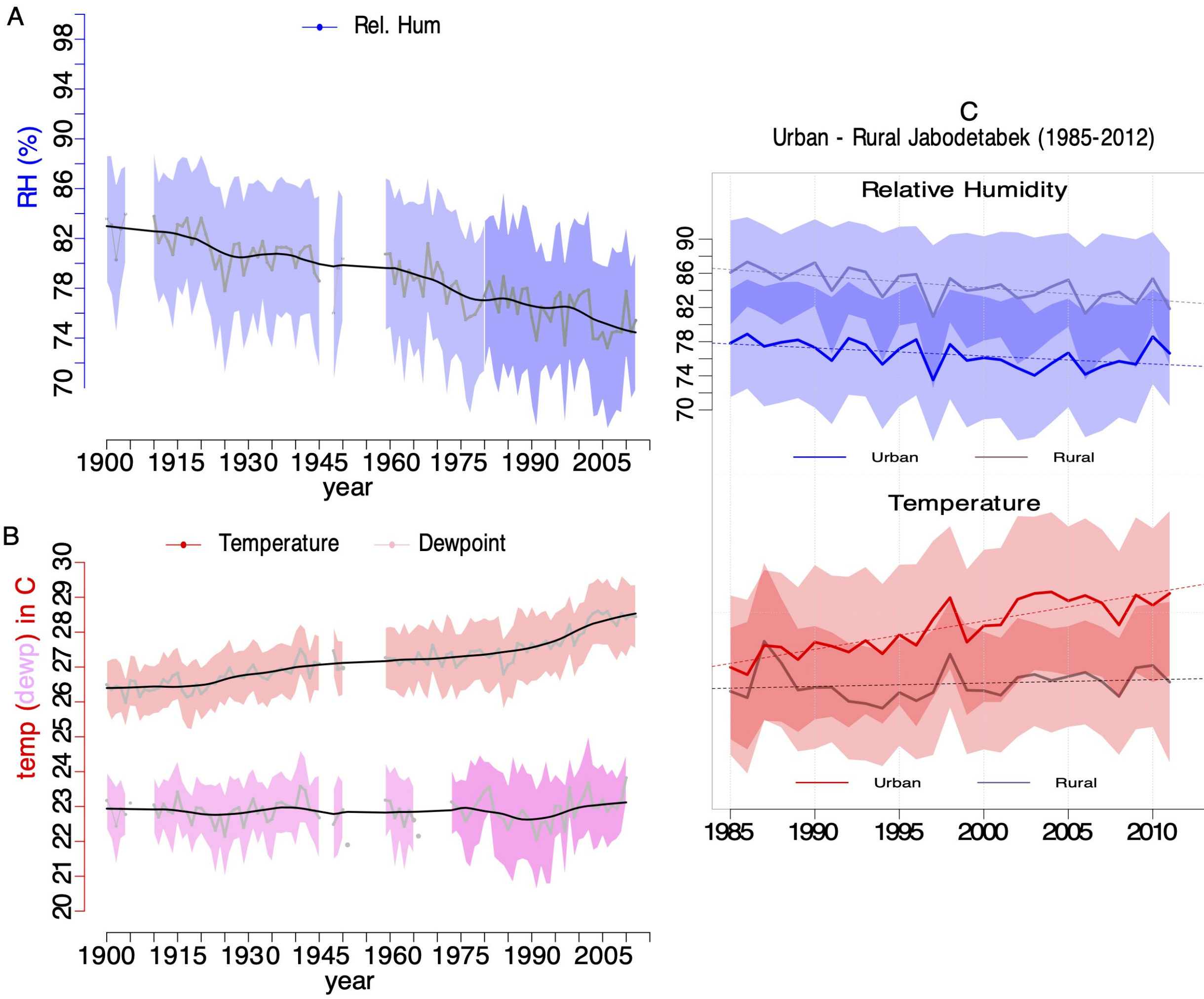

Fig. 5. Time series of (A) annual average surface relative humidity, and (B) surface air temperature and dew point temperature collected at Jakarta Observatory from 1900 to 2010. Different sources of observations (see main text) are indicated with varying colour shades. Grey lines show annual means calculated from daily means, black lines show low-pass-filtered annual data using the Loess smoother (compatible with 10-years moving average). Shaded colours indicate the standard errors of the annual means. (C) Annual average of relative humidity (blue lines) and temperatures (red lines) for urban (thick colour) and rural (thin colour) locations. Urban data represent the average of measurements taken at BMKG' s meteorological station 1, 2 and 3 in the Jakarta city area, while the rural data represent the average of locations 7 and 8 (see Figure 1).

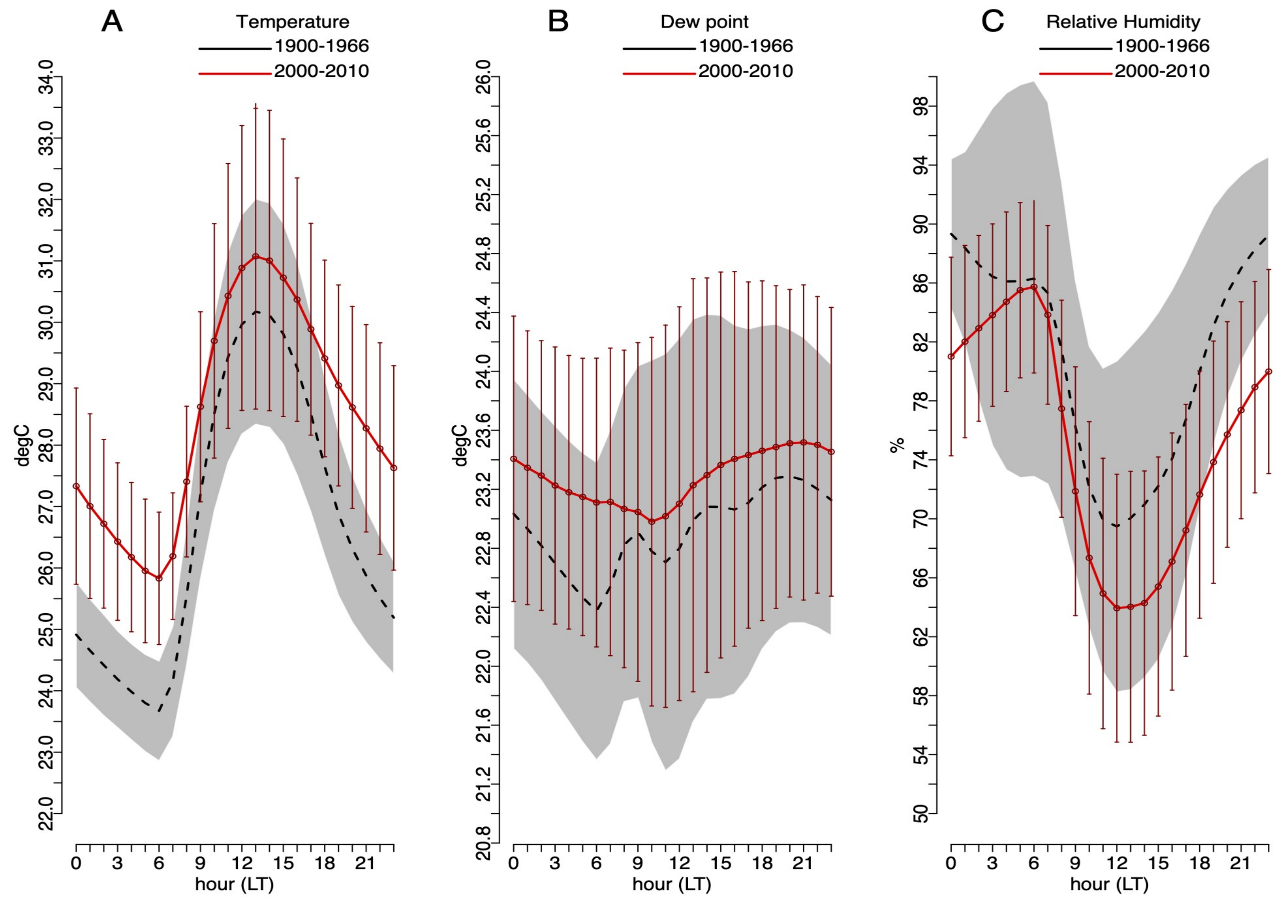

Fig. 6. Mean diurnal cycle of (A) temperature, (B) dew point temperature, and (C) relative humidity for Jakarta Obs. station for the 1900-1966 climatology and the recent decade 2000-2010. Corresponding shading and error bars indicate one standard deviation from the mean.

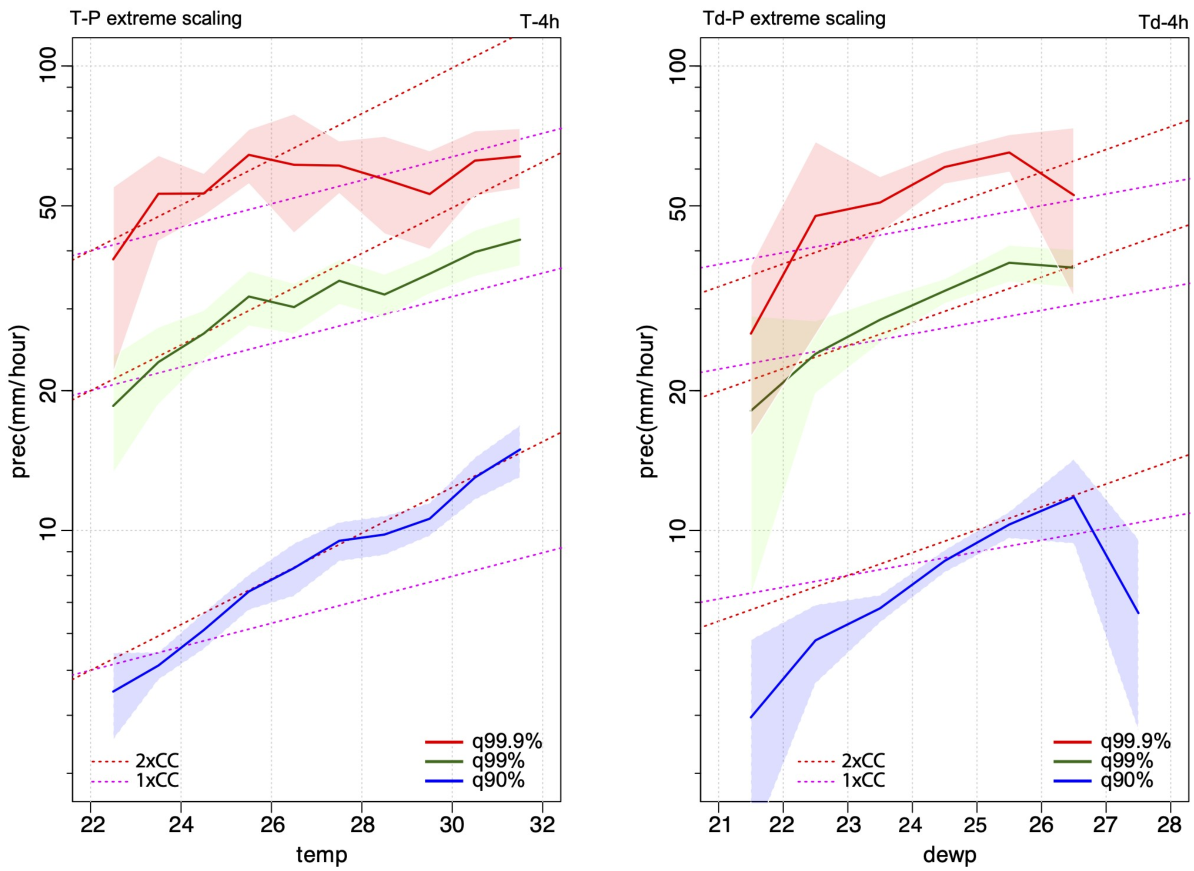

Fig. 7. Extreme precipitation as a function of temperature (T, left) and dew point temperature (Td, right) 4 hours prior to the rainfall events at Jakarta Obs. for the 90th, 99th, and 99.9th-percentiles (indicated by blue, green, and red, respectively) collected over the period 1900?2010. Shading represents 2 times the standard deviation derived from bootstrap resampling (n = 1000). Background dashed lines denote the 1CC and 2CC scaling relationships.

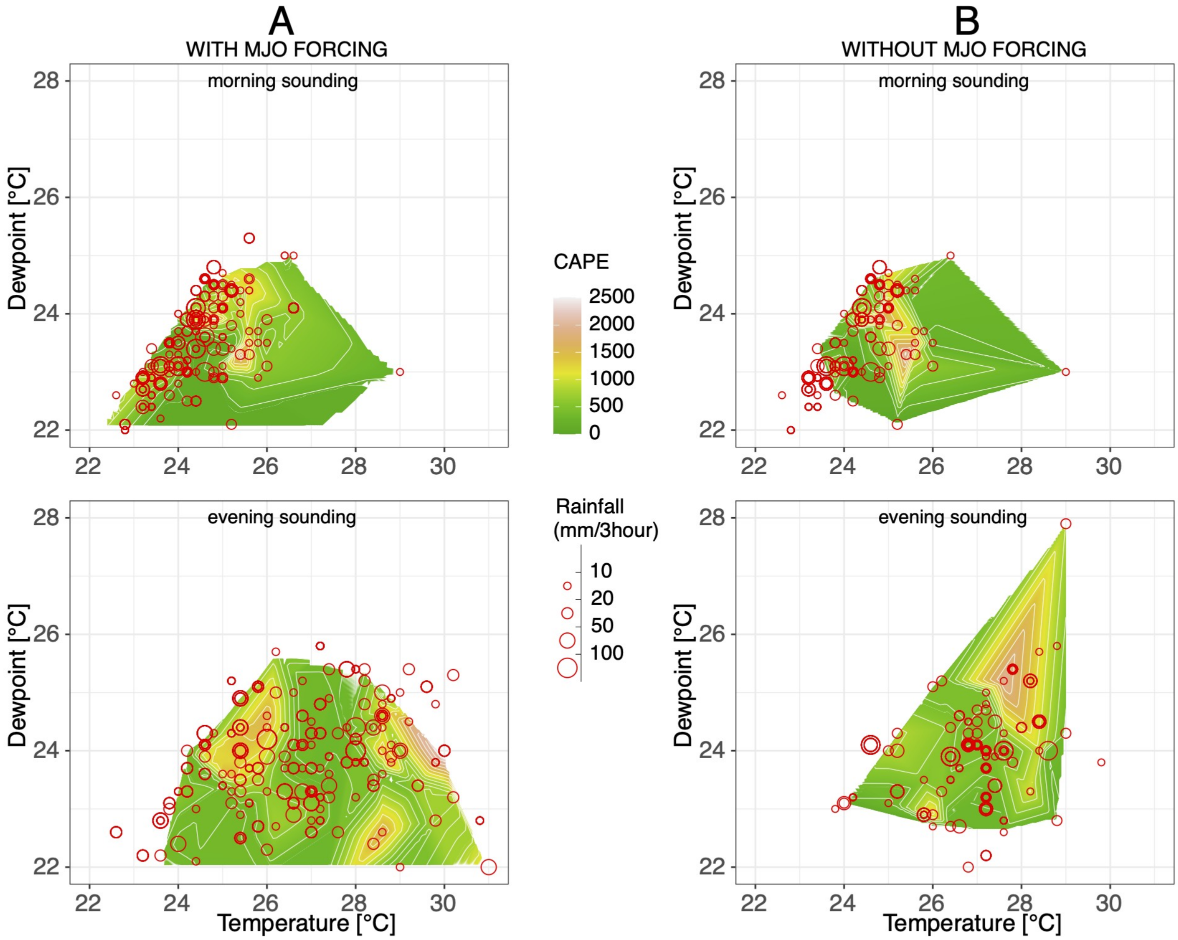

Fig. 8. CAPE (heatmap) and 3 hourly cumulative rainfall classes (circles) as function of surface temperature (T) and dew point (Td), for day-time (upper panels) and night-time (bottom panels) for periods (A) with and (B) without large-scale dynamic MJO forcing. Day-time rainfall denotes 3 hourly cumulative rainfall in the 07 – 13 LT time window, associated with the morning sounding at 07 LT; night-time rainfall denotes 3 hourly cumulative in the 19 – 24 LT time window associated with the evening sounding at 19 LT. Cumulative rainfall is collected from 3-hourly rainfall records at SHIA, Pondok Betung, Tanjung Priok, and Kemayoran stations between 2002 and 2016. Only data with an intensity exceeding 10 mm per 3 hour time interval are classified and plotted.