Do extreme precipitation intensities linked to temperature over India follow the Clausius–Clapeyron relationship?

Recent Intergovernmental Panel on Climate Change (IPCC) reports suggest that the atmosphere is getting warmer in almost every region across the globe[1,2]. As a consequence, extreme precipitation intensities (EPIs) are increasing in many regions according to the principle of Clausius–Clapeyron (CC) relationship, which states that atmospheric moisture storage capacity increases by ~7% per degree rise in temperature[3]. Therefore, the frequency of extreme precipitation events may increase with societal impacts on agriculture, economy, human health and animal habitats[4]. Several studies have been carried out on the extreme precipitation events associated with temperature over different regions which highlighted their connection to the CC relationship[5–9]. Studies over the Netherlands, Belgium and Switzerland documented that EPIs increase with temperature and follow CC scaling behaviour (which is ~7% °C) for temperatures below 8–10°C; and super-CC scaling behaviour (i.e. higher than 7%/°C) for temperatures above 10°C (refs 8, 9). A study over Australia reported that EPIs increase with temperature and exhibit CC scaling for temperatures below 20–26°C (ref. 10). Similarly, studies over Japan highlighted that EPIs exhibit super-CC for lower temperatures below 10°C and negative-CC scaling for higher temperatures above 19–21°C (refs 5, 6). A study over United States reported that extreme precipitations exhibit sub-CC scaling over western regions and super-CC scaling over eastern and northern regions[11]. These studies clearly indicate that the extreme precipitations increase with temperature and follow CC scaling behaviour over their regions, but vary from region to region depending on the temperature. Now, the question is whether EPIs linked to temperature over India follow the CC relationship, and if so, to what extent. This study intends to answer this question by analysing Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) daily datasets over India for 1961–2007 (47 years).

APHRODITE daily observations over India at 0.5° grid resolution for the period 1961–2007 were analysed. The selected period was based on the availability of APHRODITE data for both temperature and precipitation over Indian land. The wet events were first identified based on daily precipitation intensities (≥0.05 mm/d) and paired with the corresponding day's mean temperature for each event. The precipitation intensities were then stratified to different temperature bins with 1°C interval. In other words, if the wet day's temperature satisfied the criteria (n°C ≤ the wet day's temperature < (n + 1)°C) where n is an integer, then that wet day's precipitation intensity was put into n° temperature bin. The number of samples in each temperature bin was counted and assigned as sample size of that bin. The temperature bins with less number of sample sizes may introduce some sampling error, so the minimum sample size was set to 100 based on availability of samples in most of the temperature bins. Finally, the extreme precipitation intensities (75th, 90th, 95th and 99th percentiles) were computed from each temperature bin. Similarly, EPIs linked to temperature were studied for four different decades, viz. 1965–1974, 1975–1984, 1985–1994 and 1995–2004. To obtain the rate of change of extreme precipitations (CC scaling), a least squared linear regression was applied to the logarithm of precipitations which is similar to the following equation

$$P_2 = P_1(1+\alpha)^{\Delta T}, \quad (1)$$

where P_1 and P_2 are precipitations at two different temperatures T_1 and T_2 respectively; $\Delta T = T_2 - T_1$ the change in temperature, and α is the rate of change of extreme precipitation intensities, which is equivalent to ~0.07 in case of CC and can be obtained from August–Roche–Magnus approximation for saturated vapour pressure, e_s

$$e_s = 6.11 \times \exp\left(\frac{17.62 \times T}{243.04 + T}\right), \quad (2)$$

Figure 1 illustrates EPIs (75th, 85th, 95th, and 99th percentile) linked to temperature for 1961–2007 over India. It shows that all percentiles of precipitation intensities increase with temperature up to ~26°C and then start decreasing. Similar behaviours of EPIs were also found over Australia and Japan[5,6,10]. All the percentiles of precipitations over India follow CC relationship for temperatures roughly up to 20°C; then start increasing rapidly (super-CC scaling) up to ~26°C, and finally decrease (negative-CC scaling) for temperatures above ~26°C. This indicates that extreme precipitation events linked to temperature over India can be explained from the CC relationship for temperatures roughly up to 20°C. Perhaps the moisture availability is much higher at temperatures 20–26°C than that required for saturation, which causes super-CC scaling due to the large-scale and convective precipitation in the temperature regime[8,9]. This characteristic of EPIs linked to temperature is of key importance for heavy downpours. The negative-CC scaling at higher temperatures could be due to evaporative cooling effect, because, the net water vapour storage in atmosphere increases during heavy rainfall events and cools down the air temperature. The negative scaling of EPIs at higher temperatures could be due to the fact that temperature increase does not increase water vaopur endlessly in the atmosphere which is required to maintain CC relationship[12]. Seasonal analysis may explain more detailed characteristics of EPIs linked to temperature which is planned to be discussed in our next study.

Figure 2 represents the 99th percentile of EPIs linked to temperature over India for four different decades, viz. 1965–1974, 1975–1984, 1985–1994 and 1995–2004. The EPIs linked to temperature at 75th, 90th and 95th percentiles were also computed and it was found that all the relationships have similar behaviour; thus these are redundant from the figure. Similar to the results for 1961–2007 (explained in the above paragraph), EPIs linked to temperature in each decade exhibit CC relationship up to a certain temperature, then supper-CC scaling and finally negative scaling. This indicates that the relationship of EPIs with temperature computed from 47 years dataset was consistent with that from decadal analysis. However, the rate of

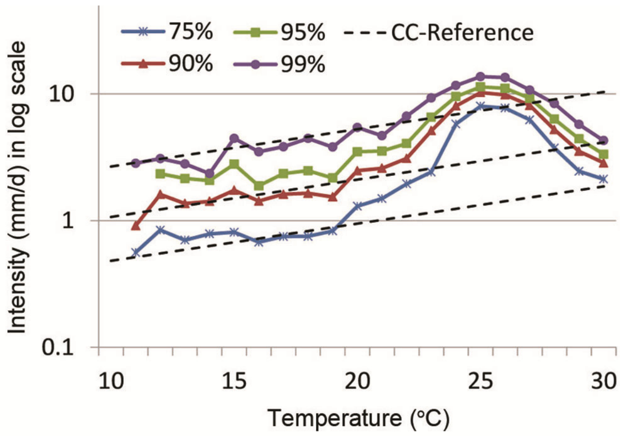

Figure 1. Extreme daily precipitation intensities of wet events (≥0.05 mm/d) as a function of daily mean temperature computed from APHRODITE observation for 1961–2007 over India.

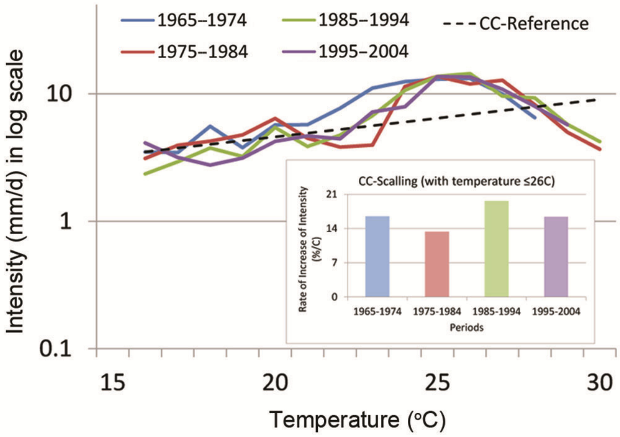

Figure 2. The 99th percentile of daily precipitation intensity of wet events (≥0.05 mm/d) as a function of daily mean temperature computed for four decades, viz. 1965–1974, 1975–1984, 1985–1994, and 1994–2004 over India. The inset figure represents the CC-scaling (considering the temperatures ≤26°C) computed for each decade.

change of 99th percentile of EPIs (α in eq. (1)) was not the same for each decade (see the inset figure in Figure 2). The rates of change of EPIs associated with the temperature below 26°C, i.e. at which the peak intensity occurs were analysed. The increasing rates of EPIs (99th percentile) were found to be 16.5%/°C during 1965–1974, 13.3%/°C during 1975–1984; 19.6%/°C during 1985–1994; and 16.4%/°C during 1995–2004. This indicates that the rate of increase of EPIs over India was found to be in the range 13.3–16.5%/°C (super-CC scaling) in the first two decades, which is increased to 16.4–19.6%/C in the next two decades. The rates of extreme precipitations (99%) with different temperature thresholds, viz. below 20°C, between 20°C and 26°C, and above 26°C were also analysed for the period 1961–2007. Results indicate that the CC scaling for each threshold varied as ~7, ~24, and about –25%/°C for the temperatures below 20°C, between 20°C and 26°C, and above 26°C respectively.

In conclusion, EPIs increase with temperature over India up to a certain degree (~26°C) and exhibit CC scaling for temperatures below ~20°C; super-CC scaling for the temperatures 20–26°C; and negative-CC scaling for higher temperatures (above ~26°C). The increasing rate of EPIs was found to be more than twice that expected from the CC relationship and higher in recent decades (1985–1994 and 1995–2004) compared to that of in earlier decades (1965–1974 and 1975–1984). This indicates that the intensification of extreme precipitations is more likely in the present climate and may increase more in future over India. Since India has lot of geographical variations such as mountain ranges, deserts, plains, plateaus, tropical rain forests and coastal areas, further studies on this issue will be focused on different seasons and sub-regions over India.

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