LETTER

Uneven rainfall effects on small-scale economic growth: Evidence from Chinese counties

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Dear Editor,

Climate change has increased the frequency and intensity of rainfall events, which exert dramatic impacts on natural and societal systems globally.[1] Although previous studies have examined macro-economic impacts of rainfall events at large scale (e.g., global and national levels) with a focus on rainfall metrics like annual totals or mean amounts,[2] these coarse spatial and temporal resolutions are not able to capture the complexity of the local impacts of rainfall events on economic activities at small scale.[3] Compared with large-scale macro economy, rainfall events may have more significant effects on small-scale economy (such as county level).[4] County economy is functioning as a connection between urban and rural markets, of primary importance for advancing the coordination of urban and rural developments.[5] It is not only regulated by macro national policy, but also affected by the economic activities of local residents, thus serving as an essential link between macro and micro economies. However, the extent to which rainfall affects economic development at small (i.e., county) scale is largely unknown. A comprehensive assessment of heterogeneous costs of climate change in county economy and implementing mitigation measures for local governments is of great concern, given the high and region-dependent vulnerability of local societies and economies.

As a region highly susceptible to climate change impacts due to her vast population and geographical diversity, China has been experiencing frequent and intense extreme rainfall events,[6] which have caused huge economic losses over the past decades. It has been estimated that, for example, extreme rainfall induced a significant reduction in rice yield by 7.6 ± 0.9% ('±' denotes one standard error) in China during 1999–2012.[7] The financial losses attributed to hydrological disasters in China amounted to $268.64 billion between 2000 and 2022, accounting for ~30% of the total losses in the world.[8] Excessive rainfall can also inflict severe damage on public infrastructure, cause human casualties, hinder industrial productivity, and disrupt socioeconomic activities. An in-depth understanding of the resultant economic impacts of rainfall events is of great significance for sustainable high-quality economic development in China.

For the first time, here we provide a nationwide investigation of the rainfall effects on county-scale economic growth in China. We utilize the fixed effects model[9] to assess the local economic effects of different rainfall metrics (Figure 1) by using daily weather observations at 0.25°×0.25° resolution[10] and economic data of annual gross domestic product (GDP) per capita growth rate at the county scale during 2000–2021. To tailor the climate data for county-scale analysis, we aggregate daily climate gridded data to the county level by areal averaging weighted by the square root of the cosine of latitude of the grid cell. Economy data are calibrated to 2015 constant prices in RMB (Chinese Yuan) to exclude the possible impact of inflation. The county- and year-fixed effects have been considered in our estimation. The first accounts for time-invariant differences across counties, such as geographical location, cultural background, and long-term economic structure. The second flexibly accounts for the multiple variations over time that are common to all counties in China, including changes in national policy orientations, pandemics (e.g., COVID-19), and other social or natural environment changes. We also introduce day-to-day temperature variability and the function of the annual mean temperature as additional control variables in the model.[3]

We find that economic growths in Chinese counties are overall promoted by sufficient increases in annual total rainfall, but reduced by the increases in the number of rainy days, rainfall intensity, and extreme rainfall events. While lower levels of annual rainfall amount adversely affect economic growth, the effects of annual total rainfall become positive when there is sufficient annual rainfall (e.g., more than ~1000 mm; Figure 1A). The beneficial effects of annual total rainfall align with previous research that reported the positive impacts of increased total rainfall on economic development at large spatial scale (e.g., national or subnational).[3,4] Here, we reveal a feature of negative and positive effects, respectively, in small and moderate-to-large regimes of annual total rainfall amount. This feature suggests that local economies are adapted to their rainfall conditions at annual scale, but droughts with consecutively absent or small amount of rainfall are inherently damaging their economic production.

Suitable rainy days (less than ~120 days; Figure 1B) and rainfall intensity (~9.6 mm/day) benefit economic growth (Figure 1C). Nonetheless, continuous increases in the frequency of rainy days, rainfall intensity, and extreme rainfall reduce economic growth rates of Chinese counties. Especially in the case of severe annual extreme rainfall amount (e.g., > 1500 mm), it may lead to a strong reduction in economic growth rate by more than 1% (Figure 1D). It has been found in previous large-scale study that extreme daily rainfall has reduced economic growth rate and this impact maybe modulated by mean temperature, thus hotter seasons and years may reduce vulnerability.[3] While our research at small scale shows that the increases in extreme rainfall (Figure 1D) and annual mean temperature (not shown) can further aggravate its negative impact on economic growth. This result provides further evidence for the negative effects of extreme rainfall and reveals its scale-dependent differences. To the best of our knowledge, our results provide the first observational confirmation of the complex effects of rainfall at county scale. Though higher-level annual rainfall can be advantageous for county economy, this benefit is contingent upon not simultaneously increasing the number of rainy days or the intensity of extreme rainfall. These findings have important implications for local governments to take region-adaptive measures by considering local rainfall structures.

We further assess the impact of various rainfall metrics on the economic output from different sectors, to understand the various channels through which rainfall impacts the economy. Compared with the tertiary sector of the economy (service production), the primary (agricultural production) and secondary (industrial production) sectors are more profoundly affected by rainfall events. The outputs from the primary sector show greater sensitivity to annual total rainfall (Figure 1E) and extreme rainfall (Figure 1H). This offers a possible explanation for the negative impact of annual total rainfall on economic growth, given that a small amount of rainfall results in drought

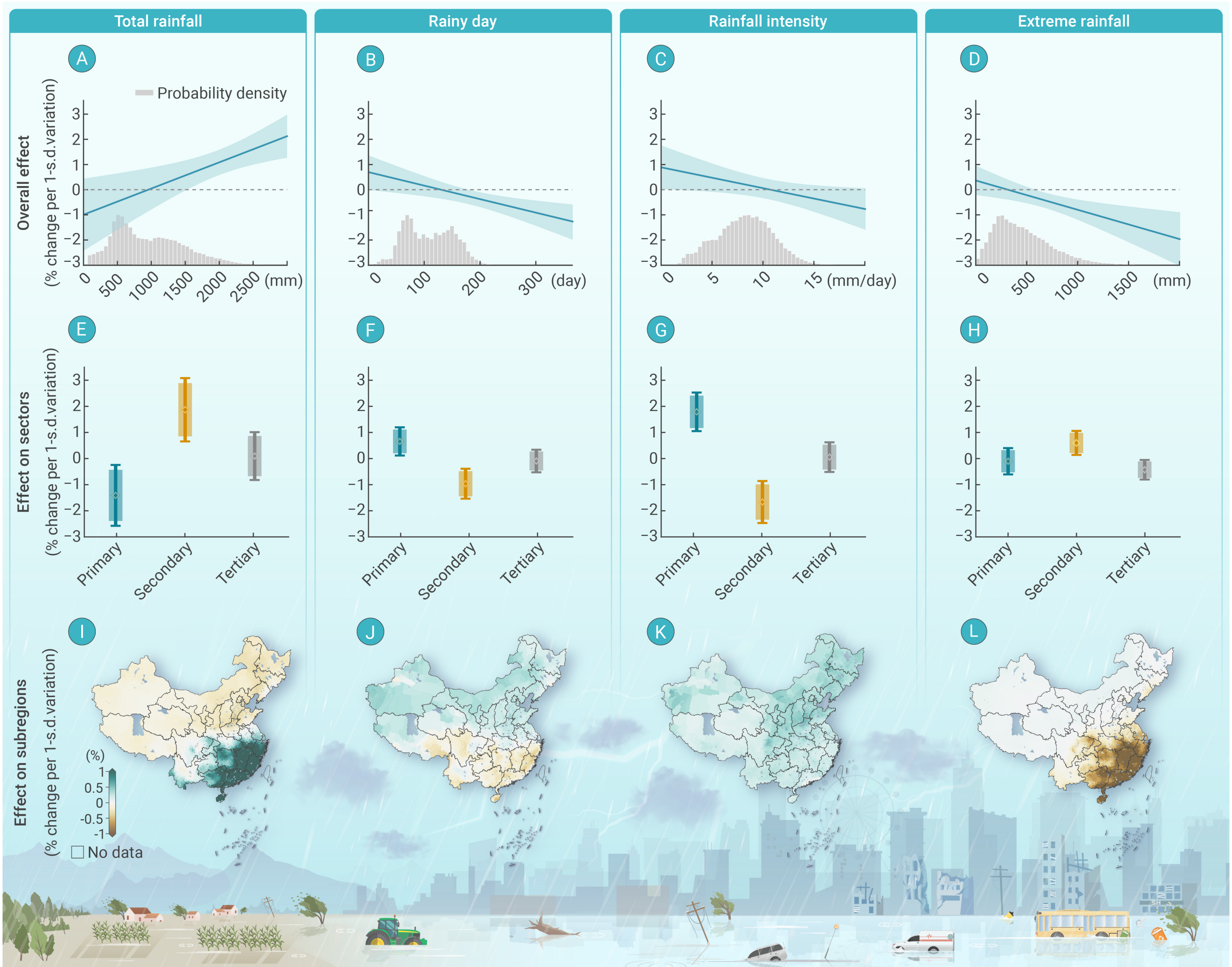

Figure 1. Effects of different rainfall metrics on economic growth rate of Chinese counties (A-D) The marginal effects of a standard deviation (s.d.) increase in the total rainfall (the annual sum of daily rainfall) (A), rainy day (the annual total number of rainy days with rainfall amount ≥1 mm) (B), rainfall intensity (the mean rainfall intensity of rainy days) (C), and extreme rainfall (the annual sum of rainfall on days where daily rainfall amount exceeds the 90th percentile calculated over the 2000–2021 period) (D) on economic growth rate (% change per 1-s.d. variation). Green shading is the 95% confidence interval, having clustered standard errors by region. Gray histograms at the bottom show the probability density distribution of each metric's sample values. (E-H) Estimates of the effect on economic growth rates of a 1-s.d. shock in different sectors. The 95% (90%) confidence intervals of the estimates are shown in bars with light-wide (dark-narrow) strips, having clustered standard errors by region. (I-L) Regional estimates of the marginal effect on economic growth rates in China. The marginal effects are calculated by fixed effects model: $G_{c,y} = \beta_1 TR_{c,y} + \beta_2 TR^2{}_{c,y} + \beta_3 RD_{c,y} + \beta_4 RD^2{}_{c,y} + \beta_5 RI_{c,y} + \beta_6 RI^2{}_{c,y} + \beta_7 ER + \beta_8 ER^2{}_{c,y} + F(T_{c,y}) + \alpha_c + \mu_y + \varepsilon_{c,y}$, where *Gc,y* is the economic growth rate calculated by the first difference of the logarithm of annual county GDP per capita. Independent variables include four rainfall metrics (TR: total rainfall, RD: rainy day, RI: rainfall intensity, ER: extreme rainfall) and their quadratic terms, as well as the function of temperature variables. α_c, μ_y, and $\varepsilon_{c,y}$ controls for the county-fixed effect, year-fixed effect, and other effects, respectively.

and extreme rainfall leads to extreme wet conditions or floods—both harm agricultural production.[7] Notably, the secondary sector exhibits a more pronounced negative response to the frequency of rainy days (Figure 1F) and rainfall intensity (Figure 1G). This may be attributed to the fact that excessive rainfall frequency and intensity can inflict damage on infrastructure and industrial equipment, thus leading to increased downtime and disrupting production, transportation, and supply activities within the secondary sector. These results highlight the importance of a well-balanced sectoral structure within local economies. A balanced sectoral structure helps enhance the resilience of local communities to mitigate rainfall change impacts, and better realize the sustainable development of the regional economy under climate change.

Both the natural environment and social development of China exhibit remarkable regional disparity, and the impact of rainfall on Chinese county-scale economic growth may also be uneven. Densely populated and economically developed regions in southeastern China are strongly boosted by increasing annual total rainfall (Figure 1I), and hindered by the number of rainy days (Figure 1J) and extreme rainfall amount (Figure 1L); while the regions with less population and slower economic development (mostly in northwestern China) show an opposite response. Specifically, over half of the counties in China, predominantly situated in the northwestern regions with a long-term lack of rainfall, encounter negative impacts of increased annual rainfall. Given their ecological and environmental vulnerabilities, a surge in annual accumulation of rainfall may lead to soil erosion and degradation of arable land to some degree. Nevertheless, a mild increase in the number of rainy days can somewhat alleviate drought conditions, fostering an environment conducive to regional economic growth. Conversely, due to the adaptation to the perennial humid environment in southeastern China, an abundance of annual rainfall cannot constitute a hindrance to economic growth there.

The impacts of rainfall intensity have been fairly balanced across regions within the economic samples (Figure 1K). However, different from previous study that found a balanced negative impact of extreme rainfall on growth rate globally,[3] the impact of extreme rainfall on county economic growth has a strong spatial difference in our study. This difference reveals the more complex uneven rainfall effects at small scale (Figure 1L). More than half of the counties of China (~51%) experience negative effects of extreme rainfall. These regions are mainly located in southeastern China where settles more than 61.65% of the national population (according to census data in 2021). Characterized by rapid development and higher economic output, southeastern China is a hotspot of enhanced climate impacts due to its dense population. One standard deviation increase in extreme rainfall amount can lead to a maximum reduction of 2.19% in the economic growth rate of the region. Due to the substantial economic output and population density of southeastern China, a slight reduction in growth rates can result in significant economic losses there. Therefore, it is important for policymakers to consider regional disparities to customize region-adaptive strategies. For instance, it is crucial for the ecologically fragile northwestern China to implement robust soil and water conservation measures to mitigate the rainfall effects. In contrast, areas particularly susceptible to extreme rainfall (e.g., southeastern China) must enhance infrastructure resilience to address the severe impacts of extreme rainfall incidences.

To summarize, we find uneven impacts of rainfall on small-scale economic growth across Chinese counties. While adequate annual rainfall benefits county economies, this advantage is predominantly observed in the southeast, whereas the northwest may experience negative effects. Additionally, increases in the number of rainy days or extreme rainfall adversely affect economic growth, particularly in more developed counties in the southeast and within the primary and secondary sectors. These uneven impacts of rainfall on small-scale economies suggest a more complex pattern of adaptation and mitigation strategies, which has rarely been reported in the literature. Projection of future rainfall under anthropogenic climate warming predicts significant increases in the frequency and intensity of extreme rainfall events. Our investigation of the adverse effects on economic production at the county level is therefore expected to be a starting point towards comprehensively assessing the economic costs of anthropogenic climate change. Mitigation of greenhouse gases emission is crucial for alleviating the negative impact of future rainfall events. As the world's largest carbon dioxide emitter, China plays a key role in global climate change mitigation. China's "carbon peaking and carbon neutrality" will promote sustainable and high-quality economic development, and largely benefit the mitigation of economic and societal risks of climate change. Future changes projected from climate models are subject to great uncertainty and are probably to be regionally heterogeneous. While our results suggest region-dependent impacts of rainfall events, these changes may lead to further local economic consequences in the future, which are difficult to quantify at present. Nevertheless, the uneven impacts of rainfall events revealed in our study raise a need for regionally adaptive policies and mitigation considering the local climate regimes, economic structures, and resilient infrastructures. An improved understanding is urgently needed for the adaptive capacity of local human-managed environments that are more susceptible to intense rainfall. Further investigation is required to comprehensively assess the societal and economic gains and losses from future rainfall changes. Such assessment should consider the influences on other channels including human health, energy consumption, and traffic transportation, etc.

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AUTHOR CONTRIBUTIONS

Z.H. compiled the data and drafted the manuscript. T.P., L.L., and M.L. initiated the study and designed the research. All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Economic data are obtained from the China County Statistical Yearbook and China Stock Market & Accounting Research Database at https://data.csmar.com. Climate data are obtained from the CN05.1 dataset at https://ccrc.iap.ac.cn/resource/detail?id=228. Codes are available upon reasonable request from the corresponding author.