Urban effects on precipitation: Do the diversity of research strategies and urban characteristics preclude general conclusions?

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Morgane Lalonde[1,2], Ludovic Oudin[1], Sophie Bastin [2]

[1] Sorbonne Université, CNRS, EPHE, UMR METIS, Paris, France ;

[2] LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt, France

Abstract

The urban effect on precipitation is a potential decrease or increase of precipitation upon and around urban areas induced by urban processes such as the urban heat island, aerosol emissions, or increased surface roughness. In the last 50 years, many studies have tried to characterize the influence of urban areas on precipitation, as understanding and predicting the effect would enable its mitigation with land use planning and water management. However, as the cities investigated and methodologies are numerous, the diversity of results is important. To summarize previous investigations and guide future research on the urban effect on precipitation, we review and classify the urban characteristics of studied cities and research strategies used in articles. We then analyze with machine learning the influence of these research strategies and urban characteristics on the results found by articles. Over 174 experiments from 48 articles, we find that the majority of studied cities are located in the northern hemisphere in temperate climates. The proposed classification encompasses seven categories, the dataset type, the data length, the spatial comparison, the climate type, the population as a proxy of the size, and the altitude and distance to the coast as proxies of geographical settings. We find that the results are mostly sensitive to the dataset type. Modeling studies, and those using rain gauges and satellite data agree on an increase in precipitation caused by urban areas while studies based on radar data do not reach a consensus since many of them do not identify an effect. The urban effect seems to be occurring more in temperate climates than in continental climates. The population and the data length are not found to impact the experiments' conclusions. The findings support that future research should focus on multi-city analysis with transferable methodologies to be able to understand the urban effect variations between cities.

Keywords

Urban precipitation, climate, observational study, modeling study, research strategy

1. Introduction

Urbanization is a massive and global ongoing phenomenon caused by diverse reasons such as global population growth, population migrating from city centers to peri-urban areas, lower number of individuals per household (Vesterby & Heimlich, 1991), and also depends on political choices (Li et al., 2021). Urbanization leads to an increased concentration of population and therefore increased vulnerability concerning natural risks, particularly flood risk. Urban areas might also modify flood hazards through modification of regional climate and particularly extreme precipitations. While the effect of urban areas on precipitation was observed by Horton 100 years ago (Horton, 1921) and studied extensively for about 50 years (Huff et al., 1972), this effect is still largely misunderstood in terms of the physical processes involved and hardly quantified by empirical observations. As urban sprawl is expected to increase in the next decades, understanding how and how much precipitation is modified by urban areas is crucial for authorities to develop and implement adaptation measures to minimize risks related to these modifications. Urban areas might impact precipitation through diverse processes such as the generation of urban heat islands, the emissions of aerosols, or even the increase in surface roughness (Han et al., 2014). The impacts that are commonly expected are an increase in precipitation over urban centers (Mohapatra et al., 2021; Sátyro et al., 2021) and over downwind areas

(Daniels et al., 2016; Le Roy et al., 2020). Nevertheless, various studies found more contrasting results, reporting in some cases a decrease in precipitation or no impact (Abdemanafi, 2017; Argüeso et al., 2016; Freitag et al., 2018). Kingfield et al. (2018) while investigating different cities in the USA neither systematically found an impact on precipitation, they concluded that the impact exists under specific environmental conditions. Some review papers intended to synthesize the diverse results obtained by case studies. A seminal review was published in 1969 (Changnon, 1969), and focused on seven large cities in the USA. The author noted that rainfall amounts were enhanced over urban areas compared to nearby rural areas but he also pointed out that this enhancement was largely variable across studied cities, possibly due to regional environmental factors (climate, topography). He stressed the need to increase the density of urban weather stations as the lack of accurate precipitation and wind data limited his analysis. Liu & Niyogi (2019) proposed the first meta-analysis of previous studies on this issue, reviewing 48 articles representing 85 studies. Their dataset consisted of a majority of cities in the USA and China (Atlanta and Beijing represent 14% and 16% of the reported studies, respectively). They quantified the change in precipitation over the 85 studies and found that mean precipitation is enhanced by 18% downwind of the city, 16% over the city, 2% on the leftwind, and 4% on the rightwind. They also found that rainfall enhancement occurs approximately 20–50 km from the city center.

Such a quantitative synthesis of the effect of urban areas on precipitation is not an easy task since previous studies did not investigate a unique and homogenous variable: some authors focused on precipitation amount, others on precipitation intensity or occurrence. The methods used to assess the effect of urban areas on precipitation were also diverse among previous studies. Lowry (1998) proposed a classification of these methodologies into 6 classes, (i) the comparison of precipitation between two points for a given period (e.g. 1 hour, 1 day), (ii) the comparison of precipitation time series between different points (e.g. over 3 decades), (iii) the descriptive analysis of precipitation maps, (iv) the correlation analysis between precipitation and other variables, (v) simulations of urban precipitation (all types of models such as urban climate models, regional climate models, or numerical weather prediction models), and (vi) the hybrid method which is the combination of two or more of the previously mentioned methods. He pointed out that despite numerous case studies and increased spatiotemporal resolution of data, the analytical methods remained rudimentary. Then, Shepherd (2005) reviewed investigations of the 1990-2005 period. He highlighted that only a relatively few numbers of numerical model studies of the urban effect on precipitation existed in the literature at that time. To do their meta-analysis, Liu & Niyogi (2019) classified the studies into four categories: (i) case studies or climatological studies, (ii) observational studies or modeling studies; (iii) the seasons analyzed; (iv) and finally, eventual diurnal cutting, i.e. some studies focused on daytime and/or nighttime precipitation.

There were also some reviews investigating the mechanisms involved in the modification of precipitation due to urban areas. Han et al. (2014) proposed an exhaustive review of the different hypotheses or causes and mechanisms of urban effects on precipitation. Even if these mechanisms are listed in many studies' introductions since the 60s, they evolved in their formulation and became clearer through time. Han et al. (2014)showed that urban heat island, surface roughness, and aerosol concentration are the main causes of precipitation modification due to urban areas, the authors also detailed how recent studies contributed to the understanding of each source of urban effects on precipitation. The last review was published in 2021 and investigated specifically the dynamical effects of cities on precipitation (Yue et al., 2021). The authors pointed out that currently, the scientific literature does not agree on the effect of cities on precipitation, even if an impression of increased precipitation consensus can be felt over the studies. They noted that this is especially true regarding tropical cyclones. They concluded that the impacts of urban areas on precipitation are complex and differ for each city with different characteristics and geographical settings as well as being closely related to the characteristics of weather systems or seasons.

Reviews agree on the existence of an urban effect on precipitation but relate the complexity of generalizing it as it varies a lot across cities (Ganeshan et al., 2013). First, studies investigated different urban areas which have different sizes and lie in regions with different climates and rainfall patterns. Climate may influence the dynamics of the urban effects on precipitation and thus its quantification. The impact may also be a function of the size and morphology of cities. Then, the quantification of the urban effects may vary because of the different methodologies and data used in the studies. From the currently existing literature, it is not trivial to identify whether the diversity of the results on the effect of urban areas on precipitation comes from differences in local climates and local characteristics (such as the morphology or geographical settings) or differences in the data and methods used by the authors. Based on this observation, we aim at analyzing the results of the experiments made in the past studies, with a joint analysis of the cities' characteristics (such as the climate, the population, or geographic settings) and research strategies (such as the data and the method used to quantify the urban effect on precipitation) of each experiment, and thus investigate the complexity of urban effects highlighted by Yue et al. (2021). As such, in the present study, by a detailed analysis of the articles investigating urban effects on precipitation published over the last 50 years, we classify the different research strategies selected by the authors and the characteristics of the studied urban areas. Then we statistically analyze the relationship between the results of these studies and their urban characteristics and research strategies through classification trees.

2. Data and method

2.1. Dataset constitution

To collect the most exhaustive dataset of studies investigating urban-related precipitation impact, we ran an evasive search string on Web of science without specifying a limited period.

Search string = (TI = (Urban) OR TI = (City) OR TI = (Cities)) AND (TI = (rainfall) OR TI = (precipitation))

The search string found 1222 results, i.e. possible articles to include in our study. Then, we read the titles and abstracts of these 1222 articles and selected 140 that investigated urban effects on precipitation and thus being relevant to our study. As the search string was generic it was expected that the number of articles fitting our study reduced a lot from the original dataset. The original dataset included other types of studies, for example, investigations on the chemical characteristics of urban rainfall. We further read in detail these 140 articles and found 48 of them that were sufficiently detailed in terms of data, methods, and main conclusion on the identified or not urban effects (precipitation increase, precipitation decrease, or no impact on precipitation). An article may present single or several assessments of the effect of urban areas on precipitation, e.g. applying the same method to several cities or applying several methods to a single city. Therefore, instead of referring to articles, we will refer to experiments. Throughout the 48 articles, we identified 174 experiments conducted over 40 urban areas. As shown in Figure 1, the 40 studied urban areas are mostly located in North America, Asia, and Europe, almost all of them are in the northern hemisphere, and the majority of cities are in coastal areas. Still, during the selection of articles, we found a few of them focusing on the southern hemisphere, two studying African urban areas, Nairobi in Kenya (Ongoma et al., 2015), and the Middle-Eastern Region in Tanzania (Anande & Park, 2021), one in central America (Jauregui & Romales, 1996), two south American cities, San Miguel de Tucumán in Argentina and Manaus in Brazil (Freitag et al., 2018; Sátyro et al., 2021), and one article for Oceania investigating Australian urban areas (Rosenfeld, 2000). However, these listed articles could not be selected for the analysis in this article because of their methodology or dataset types descriptions, or inexplicit conclusions. The map also indicates that some climates such as the Temperate climate are intensively represented while others are not represented at all. In table 1, we present the 48 articles selected for the review, along with some basic information on datasets types, temporal scale, and climate type (categories are further detailed in the results section).

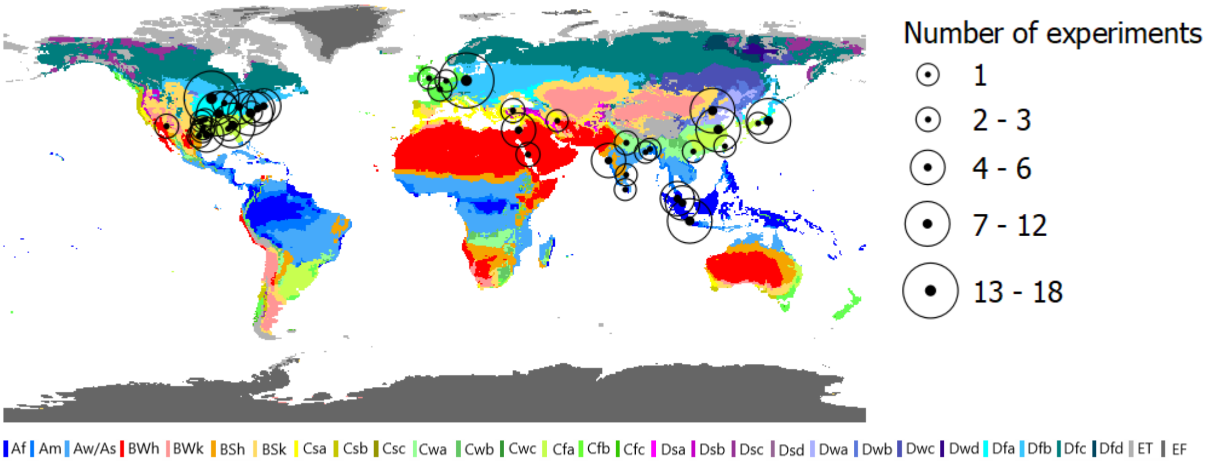

Figure 1. Map of the 174 experiments' locations from the articles' dataset. The circles are centered on studied cities, the size of the circles indicates the number of experiments for each city (see legend), and the colormap represents the climate of the area according to the Köppen classification.

Table 1. Articles selected for the review are classified by the datasets types, temporal scale of investigation (case studies are experiments focusing on a single precipitation event while climatological studies assess the effect of urban areas on precipitation in the long term), and climate type (the first level of the Köppen classification).

Data	**Temporal scale**	**Climate**	**Articles**
Raingauges	Climatological study	Temperate	(Abdemanafi, 2017; Changnon, 1979, 1980; Çiçek & Turkoglu, 2005; Huff, 1975; Huff et al., 1972; Huff & Changnon, 1973; Huff & Vogel, 1978; Vogel & Huff, 1978)
		Continental	(Dou et al., 2015; Yang, Tian, et al., 2014)
Radars	Climatological study	Temperate	(Dixon & Mote, 2003; Ganeshan et al., 2013; Le Roy et al., 2020; Manola et al., 2020)
		Continental	(Perryman & Dixon, 2013)
	Case study	Temperate	(Lorenz et al., 2019)
Satellites	Climatological study	Temperate	(Hand & Shepherd, 2009)
Models	Climatological study	Temperate	(Kusaka et al., 2019; Rose et al., 2008; Sarangi et al., 2018; Seino et al., 2018; Shafir & Alpert, 1990; Shepherd, 2003; Shepherd et al., 2002; Shimadera et al., 2015; Song et al., 2016)
		Desertic	(Luong et al., 2020)
		Savanna	(Shastri et al., 2019)
		Equatorial	(Argüeso et al., 2016; Doan et al., 2021)
	Case study	Temperate	(Bélair et al., 2018; Carraça & Collier, 2007; Debbage & Shepherd, 2019; Hosannah & Gonzalez, 2014; Matheson & Ashie, 2008; Ntelekos et al., 2008; Pathirana et al., 2014; Shafir & Alpert, 1990; Shem & Shepherd, 2009; Souma et al., 2013; Xiao et al., 2020)

		Continental	(Miao et al., 2011; Yang, Smith, et al., 2014; Yu et al., 2017; Yu & Liu, 2015; Zhong & Yang, 2015)
		Desertic	(Luong et al., 2020; Yang et al., 2019)
		Savanna	(Simpson et al., 2008)

2.2. Classification

To perform the classification of the referenced 174 experiments, we first extracted and classified key information from the articles and then regrouped them into categories. In the present study, we identified two general categories, (i) city characteristics, and (ii) research strategies. For city characteristics, we retained three subcategories, (i) the climate zone, (ii) the population as a proxy of the size of the city extent, and (iii) the geographic characteristics. For the geographic characteristics, we used as proxies the altitude of the city and its distance to the coast. For research strategies, we set four subcategories: (i) the dataset type (radar, rain gauge, satellite, or model simulation), (ii) the data length (analysis over a single precipitation event or long-term analysis), and (iii) the spatial comparison, and (iv) the additional variables used. We detail these categories in part 3.1 of the results. Based on the classification, for each experiment, we registered which categories it belongs to.

2.3. Analysis

The relationship between the main conclusions drawn from the retained experiments and the settings of these experiments is assessed in this study through machine learning of classification trees. Classification trees are classical tools for both exploratory data analysis and predictive applications (Myles et al., 2004). A classification tree predicts the value of a target variable based on several input variables. In this study, the target variable is the outcome of an experiment (urban areas lead to an increase in precipitation, a decrease or no impact) and the input variables are the several previously identified classification variables (the climate zone, the population, the altitude, the coast distance, the dataset type, the data length, and the spatial comparison). A decision tree is constructed by recursively partitioning the experiments by a set of decision rules to provide an informative and robust hierarchical classification model. Classification trees present the advantages for our study in that both continuous and discrete (categorical) input variables may be used and the obtained classification tree is interpretable through the input variable selected at each splitting node and through the overall importance of each input variable. A Classification tree also provides a level of confidence, the accuracy, which is the number of correct predictions made divided by the total number of predictions made, multiplied by 100 to turn it into a percentage. The classification tree algorithm used in the study is the CART algorithm (Breiman et al., 1984) and we used the rpart function in R (Therneau & Atkinson, 2022) with cross-validation.

3. Results

3.1. Diversity of research strategies and urban characteristics

3.1.1. Cities' characteristics

As mentioned before, three subcategories are used to characterize the cities: the climate zone, the size, and the geographical environment.

Climate. Following the Köppen climate classification, 12 of the 30 existing climates are present in our studies' dataset (Fig.1). To later analyze the potential influence of these climates on the urban effect on precipitation, we only used the 5 climate types corresponding to the first level of the Köppen climate classification. As shown in Fig.2, of the 174 experiments, 35 are in continental climates, 4 in dry climates, 22 in tropical climates, and 113 in temperate climates. The Polar climate is not represented in our dataset.

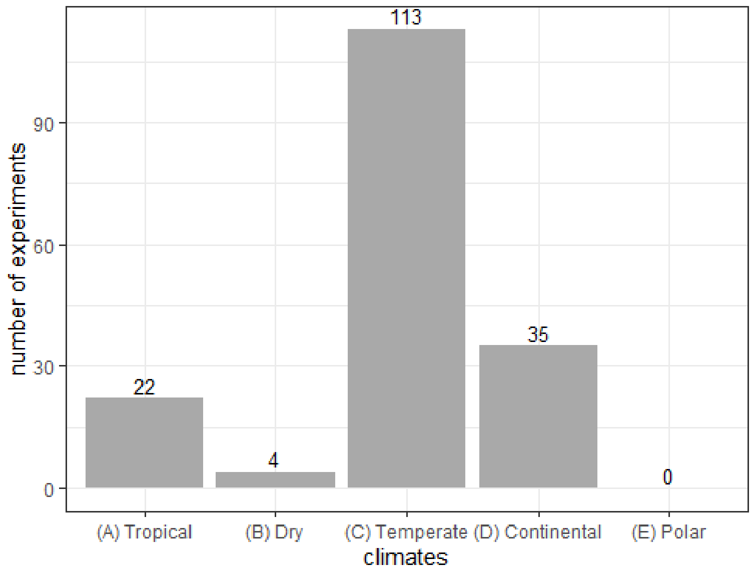

Figure 2. Climates present in the dataset of 174 experiments

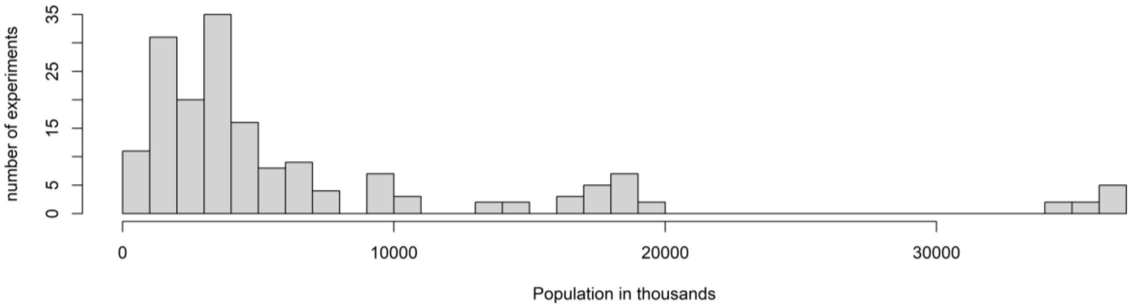

Figure 3. Population distribution of the 174 experiments.

City size. As the definition of urban land use is highly variable, and as a dataset covering all of our cities could not be found, we decided to use population data of the cities at the year of the experiment as a proxy. We used the “Annual Population of Urban Agglomerations with 300,000 Inhabitants or More in 2018, by country, 1950-2035 (thousands)” of the World Urbanization Prospects 2018 (United Nations). In Figure 3 we present the population distribution of the 40 urban areas studied in our dataset of 174 experiments.

Geographical environment. To categorize cities into different geographical environments, we used two numerical variables to describe them: the altitude and the distance to the coast. In figure 4 we present the distribution of these two geographical variables. The majority of cities are coastal and thus close to the sea level.

3.1.2. Research strategies

For the research strategies, four subcategories are considered.

Data type. Among the 174 experiments, precipitation data come from four different types: rain gauges, weather radars, satellites, and models. The different observational data do not provide the same types

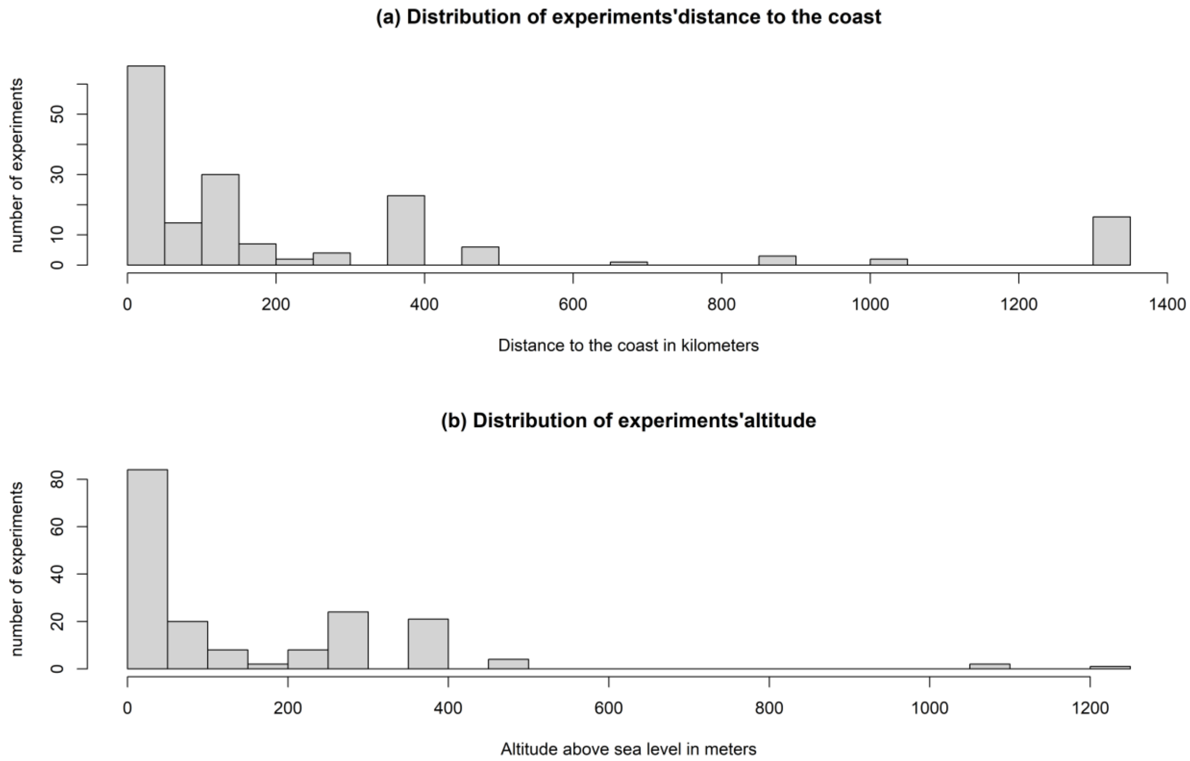

Figure 4. Geographical settings of the 174 experiments, with (a) their distance to the coast in kilometers and (b) their altitude in meters.

of precipitation measurements and the uncertainties associated with estimated precipitation are different. Rain gauges provide accurate point rainfall estimates near the ground surface but they hardly capture the spatial variability of rainfall. Radars on the opposite lack accuracy (mainly for light precipitation and over orography) but capture well the spatial variability of rainfall fields(Ochoa-Rodriguez et al., 2019). Still, some experiments used radar products merged with rain gauges data such as the Stage IV precipitation dataset (Lin & Mitchell, 2005) used by Ganeshan et al. (2013) or RADOLAN (DWD, 2017) used by Lorenz et al. (2019). Modeled precipitation is an output of a numerical model which relies on several parametrizations. Numerical models can induce errors but they are regularly validated against different datasets and they allow to reach fine spatial and temporal resolutions. Among the models used in the experiments, one model, in particular, is heavily used with its different possible parametrizations, the weather research and forecasting (WRF) model (Anande & Park, 2021; Argüeso et al., 2016; Debbage & Shepherd, 2019; Freitag et al., 2018; Kusaka et al., 2019; Luong et al., 2020; Miao et al., 2011; Niyogi et al., 2020; Ntelekos et al., 2008; Pathirana et al., 2014; Sarangi et al., 2018; Shem & Shepherd, 2009; Shimadera et al., 2015; Song et al., 2016; Supantha et al., 2018; Wang et al., 2016; Xiao et al., 2020; Yang, Tian, et al., 2014; Zhong & Yang, 2015). However, the experiments using the WRF model are not directly comparable with each other because of the diversity of parametrization used. Despite the numerous types of models used for the experiments (urban climate models, numerical weather prediction models, global and regional climate models) and the numerous possible parametrizations of the urban areas for a given model, we did not sub-classified this variable since it would have yielded too many possible values for this class and consequently larger uncertainties in the classification trees. Among the 174 experiments retained in this study, 64 used radar data, 87 used model data, 22 used rain gauge data, and one used satellite data.

Other variables than precipitation are used depending on the method selected for the experiment, such as wind, land use, temperature, aerosols, roughness, latent and sensible heat fluxes, topography, soil moisture, and air humidity. They can be used in observational studies for wind-based analyses or correlation analyses (details in next paragraph) or in modeling studies as variables that will be modified to simulate urban effects.

Spatial comparison. In general, the outcome of an experiment (i.e. a qualitative or a quantitative statement on the effect of urban areas on precipitation) is based on the comparison of precipitation for different locations around or over the urban areas. Four types of spatial comparisons exist throughout the experiments. Some are based on a comparison of precipitation in rural and urban areas, or areas of different levels of urbanization. Many experiments followed wind-based analyses for which precipitation is compared on zones delimited by their location concerning urban areas and wind direction. Generally speaking, the precipitation from upwind areas is used as a reference, and precipitation either downwind or over urban areas is compared to this reference. Among the 174 experiments retained in this study, 53 used rural/urban comparisons, 23 used the comparison of different levels of urbanization, 60 used upwind/downwind comparisons, and 38 used upwind/urban center comparisons.

Data length. The precipitation data used in the articles have different lengths independently of their type (rain gauges, radars, satellites, models). Some articles used precipitation statistics obtained over a relatively long period typically from one year to several decades (Hand & Shepherd, 2009; Manola et al., 2020), while others only used a day or a week of data (Debbage & Shepherd, 2019; Lorenz et al., 2019) generally corresponding to a particular precipitation event. Following the classification by Liu & Niyogi (2019), two classes were considered: the first one is the climatological scale for the analyses dealing with data from one-year length to several decades and the second one is the case study for the analyses focusing on a specific precipitation event (lasting from a few hours to a few days). As shown in Table 1 the majority of experiments belonging to the case study class are numerical modeling experiments. This scale offers the possibility to study how the dynamic of a precipitation event (convective event, thunderstorm) evolves with different urban processes such as the urban heat island, or the important surface roughness. Among the 174 experiments, 123 were climatological studies and 51 were case studies.

Other characteristics that appeared important throughout the reading of the articles were not retained in our analysis since they would have produced too many categories or were too vaguely described to be included in our classification proper categories. Among these characteristics, we find for instance the target period of precipitation that can be a specific season or a range of hours within the days, such as the precipitation over the day/night periods or weekday/weekend (Çiçek & Turkoglu, 2005; Huff & Changnon, 1973). In the present study, we study the effect of urban areas on precipitation independently of the seasons and we also focus on summer precipitation as many articles only studied this season, the rationale being that the effect is expected to be stronger in summer when intense and convective precipitation events occur (Yue et al., 2021).

3.2. Analyses

In this section, we analyze with machine learning the conclusions of the 174 experiments coming from 48 articles. Three possible conclusions exist: (i) urban areas increase precipitation, (ii) urban areas decrease precipitation, and (iii) urban areas do not modify precipitation. We focus on these qualitative assessments rather than the quantitative ones since there were too many differences in the way each experiment quantified the urban effect on precipitation. As such the qualitative conclusion on the effects of urban areas on precipitation may refer to rather different statistical characteristics: the occurrence, the intensity, and maximum or mean values. Fig. 5 presents the number of experiments and their main conclusions for (a) all of the experiments, and (b) the experiments focusing on summer precipitation. Among the 174 experiments registered, about 71% of them found an increase while 19% found no impacts, and 10% a decrease. For summer experiments 63% of them found an increase while 23% found no impacts, and 14% a decrease.

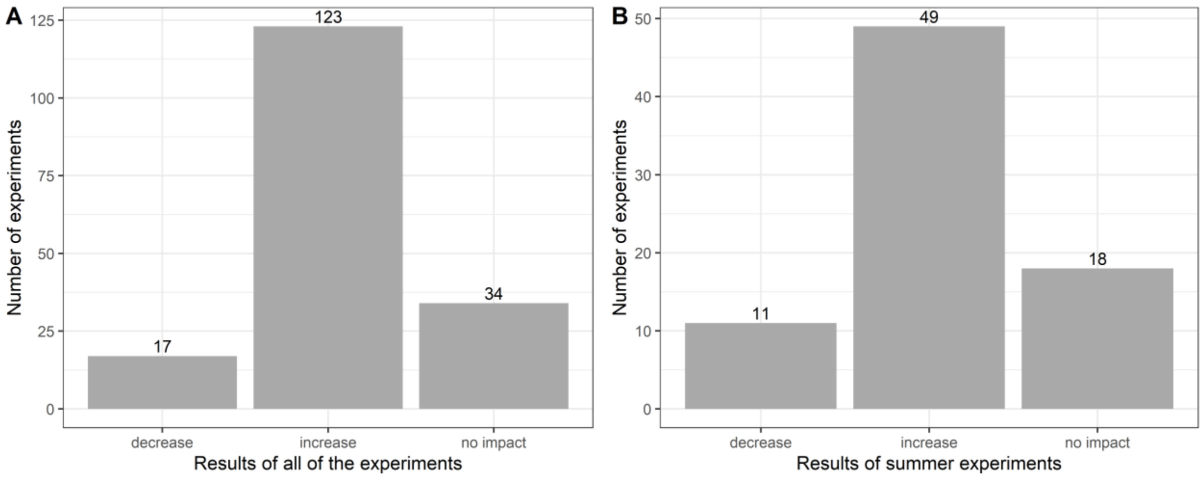

Figure 5. The main conclusion on the effect of urban areas on precipitation is drawn by (a) all the experiments, and (b) summer experiments.

We grew classification trees based on seven variables that we summed up in Table 2 and explained in the previous section. The "Data" variable can be a Rain gauge, Radar, Satellite, or Modeled. The "Spatial comparison" variable can be Upwind/Urban, Upwind/Downwind, Urban/Rural, or Urban/less urban. "Climate" can be tropical, dry, temperate, or continental. The "Data length" indicates if the experiment is a climatological study or a case study. Three numeric variables are used as proxies. The "Population" variable is a proxy for the size of the city, and the "Altitude" and "Coast distance" are proxies for the geographical settings.

Table 2. Variables used for the classification trees.

Input variable	**Possible values**
Datasets types	Rain gauge; Radar; Satellite; Modeled
Spatial comparison	Upwind/Urban; Upwind/Downwind; Urban/Rural; Urban/less urban
Climate	Tropical; Dry; Temperate; Continental
Data length	Climatological study; Case study
Population	113 000 ≤ population (number of inhabitants)< 36 860 000
Altitude	0 ≤ altitude (m) < 1216
Coast distance	0 ≤ coast distance (km) < 1327

We computed two analytical models giving two classification trees. The first tree uses all of the 174 experiments, and the second the 79 experiments focusing on the summer season (see Figure 6). The accuracy of the first tree is 71.8%, and the accuracy of the second is 70.5%.

In both trees, the dataset type is the variable that explains the largest part of the variance of the conclusions drawn by the experiments. The trees identify that when radar data are employed, the conclusions are rather diverse, contrary to experiments employing other types of data that generally pointed out increased precipitation due to urban areas. Subsets of experiments grouping modeled, rain gauges, and satellite data found 80% of "increase" results in both trees, while subsets of radar data found 55% of "increase" results in the tree computing all of the experiments and 40% of "increase" results in the tree computing summer experiments. Within the experiments based on radar data, there were almost as many experiments finding an "increase" as experiments finding "no effect". These first nodes based on dataset type efficiently split the experiments into a group of experiments indicating "no effect" on precipitation (the branch concerned by data) and a group of experiments with a majority of experiments finding increased precipitation. However, the first split does not help to distinguish experiments that found decreased precipitation due to urban areas.

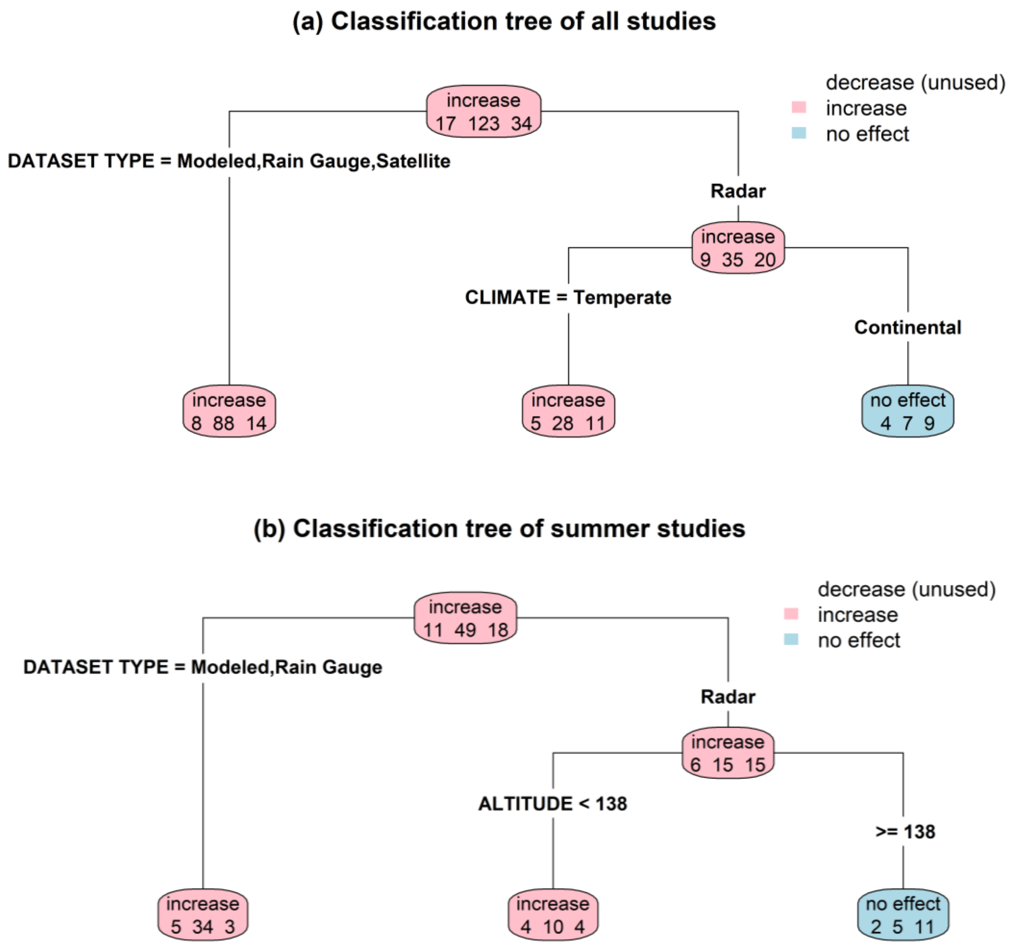

Figure 6. Classification trees of (a) all experiments' results and (b) summer experiments' results explained with 7 variables (datasets types, spatial comparison, climate, data length, population, altitude, and coast distance). The title of each box and its color indicates the dominant result, and the three numbers indicate respectively the number of studies showing a decrease, an increase, and no impact.

For the second node, both trees split the branch concerned by experiments using radar subset into two additional subsets. In the tree with all of the experiments (Figure 6), the node splits the experiments based on the climate type. Experiments using radar data in a temperate climate concluded generally that urban areas increase precipitation (28 "increase", 5 "decrease" and 11 "no effect") while experiments using radar data in a continental climate generally did not detect an effect of urban areas on precipitation (7 "increase", 4 "decrease" and 9 "no effect"), but the accuracy of the tree for this branch is rather low. In the second tree with the summer experiments, the radar data subset is split based on the altitude variable. It identifies that more than half of experiments using radar data focusing on cities located at an altitude below 138 a.s.l. found that urban areas increase precipitation (10 "increase", 4 "decrease" and 4 "no effect"), but it is still not a generality. Conversely, a majority of experiments using radar data focusing on cities located at an altitude above 138 a.s.l. found that urban areas do not affect precipitation (5 “increase”, 2 “decrease” and 11 “no effect”).

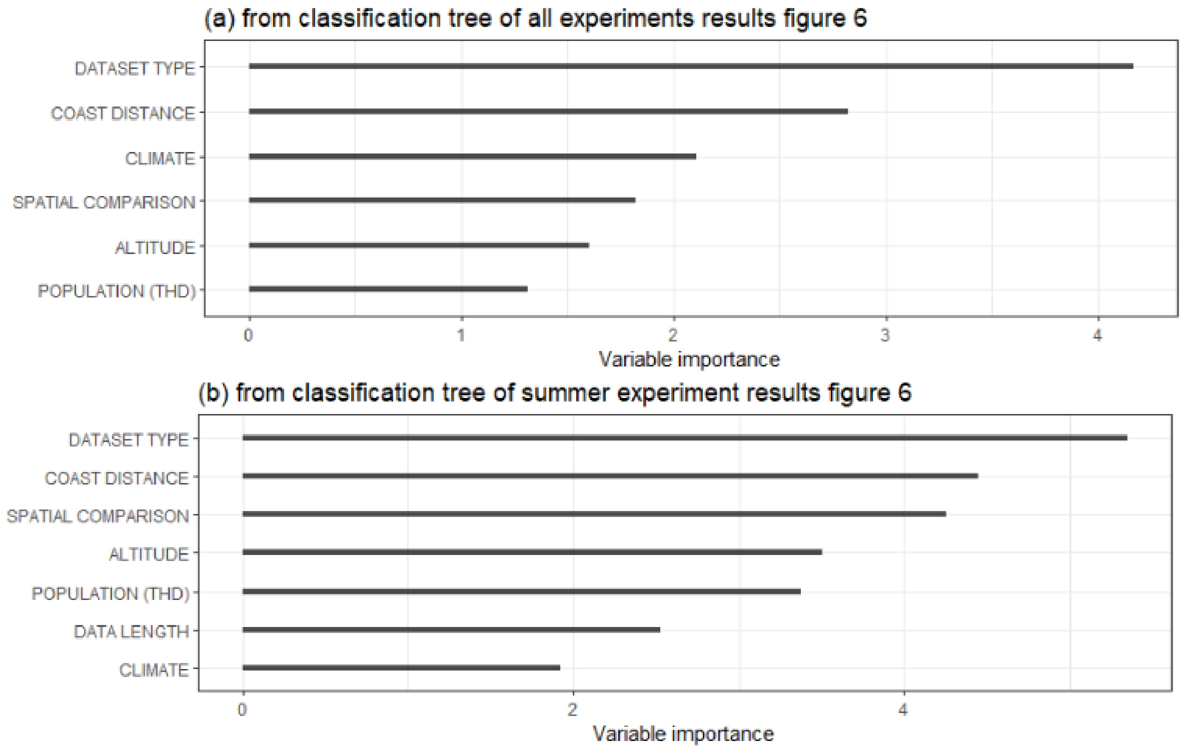

Figure 7. Variable importance in the classification trees brought by the variables from classification trees of figure 6, (a) with all experiments and (b) with summer experiments.

For both trees, the improvements in the classification trees brought by the variables are given in Figure 7. The improvement is an overall measure of variable importance which is the sum of the goodness of split measures for each split for which it was the primary variable, plus goodness for all splits in which it was a surrogate (Therneau & Atkinson, 2022). As already seen in the trees (Figure 6), the datasets type is the variable with the highest importance in reducing the variance within the results. The second is the coast distance. For both datasets, the coast distance can lower the variance even if the variable does not appear in the trees in Figure 6, but this variable is related to the altitude variable. The population and the data length are the variables bringing the smallest improvements. The spatial comparison and the altitude do bring improvements in both analytical models but are neither in the highest nor lowest contributions. Then the climate is one of the variables having the highest importance in the tree with all of the experiments, but in the tree with summer experiments, it is the variable having the smallest importance.

4. Discussion and conclusion

Our classification tries to encompass the numerous choices made by scientists such as their selection of data, and city to set up an experiment. However, a classification necessarily simplifies the great diversity of the experiments. One example is our definition of a spatial comparison that compares precipitation in upwind and downwind areas. These areas differ in their spatiotemporal definitions over most of the experiences. Their temporal definition is evolving along with the evolution of wind data resolution and availability. Older articles used a single wind direction used for all time steps (Huff & Vogel, 1978), corresponding to the main wind direction, while more recent articles used temporally varying wind directions. Besides, the definition of upwind and downwind areas knows a lot of different representations and can be considered at different altitudes. When defined as a circular area, the radius varies such as the minimum and maximum distances (from the city) may lead to areas with quite different extents. Otherwise, the upwind and downwind areas can take other shapes more or less complex (Figure 8).

Additionally, the classification corresponds to the research strategies used to this day. As both data and methods evolved through time, the representativeness of each class changed through time. For example, the available types of precipitation data evolved with time, we can see it with the evolution of data used in the experiments in Figure 9. We find the first article using radar data instead of rain gauges in 1984 (Changnon, 1984), the first using modeled data in 1990 (Shafir & Alpert, 1990), and the first using satellite data in 2000 (Rosenfeld, 2000). In the 70s, the precipitation trends due to urbanization were generally studied whereas spatial comparison approaches were developed in recent decades. For instance, Dettwiller & Changnon (1976) used 100-year records of three rain gauges in Paris (France), St. Louis, and Chicago (USA) and found upward trends reflecting climate change but also inadvertent urban effects on local convective precipitation. Indeed, the data type (rain gauges) lead the authors to deal with temporal analyses instead of spatial analyses. Rain gages experiencing urbanization with long-term records were available in different cities, even if there was only one station per city. On the other hand, only a few cities were equipped with numerous rain gauges able to represent spatial variability with fine resolution. For this reason, the only papers investigating urban effects on precipitation with spatial analysis in the 70s are all based on the METROMEX experiment regrouping the cities of St. Louis, Chicago but also Indianapolis, Washington, Cleveland, Chicago, and Houston.

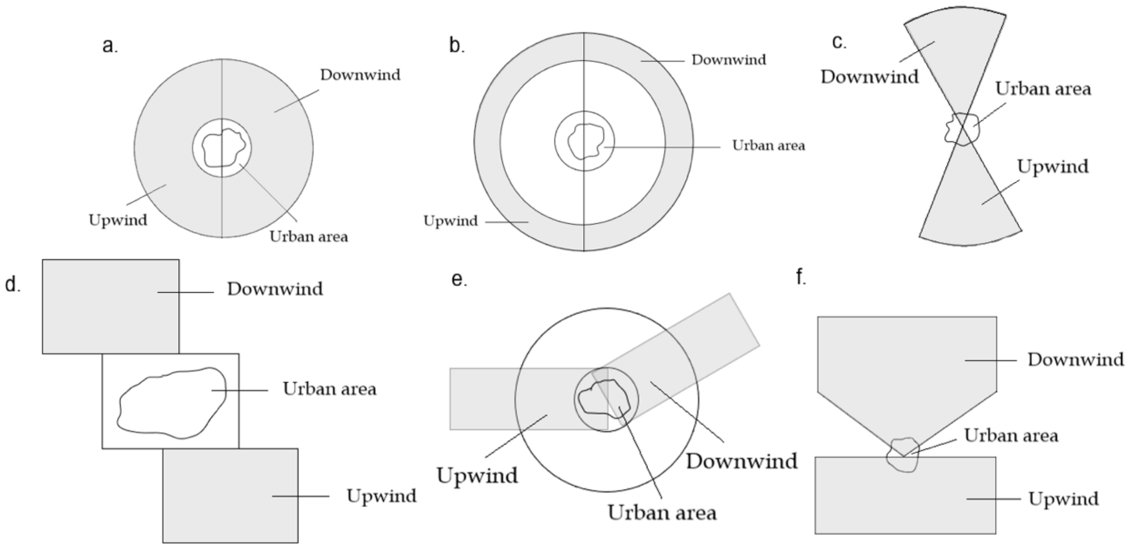

Figure 8. Diversity of spatially dynamic representations of upwind and downwind areas. a. (Perryman & Dixon, 2013) b. (Ganeshan et al., 2013) c. (Kingfield et al., 2018; Le Roy et al., 2020) d. (Sarangi et al., 2018) e. (Lorenz et al., 2019) f. (Shepherd & Burian, 2003).

Despite these limitations, our study presents a novel classification that encompasses 7 variables describing research strategies (methodological choices) as well as urban characteristics in a large sample of 174 experiments. This classification enables us to statistically analyze the conclusions drawn from each experiment depending on the variables, we scope clear outcomes:

- The conclusion on the effect of urban areas on precipitation depends on the type of data used. Liu & Niyogi (2019) noticed a potential bias coming from the type of data selected, identifying that modeling results tend to underestimate the mean impact of urban rainfall modification compared to observational studies. In our study we find the opposite: the majority of experiments using models' simulation and rain gauges data found that precipitation increases due to urban areas, while conclusions drawn for experiments using radar data are quite disparate with a large number of experiments pointing out no effect of urban areas on precipitation. Our analysis thus also enlightens on potential bias introduced by the selection of different types of data. Even if our literature review does not have the necessary tools to explain this observation, some hypotheses can be formulated, (i) results from a modeling study finding no effect might not be easy to publish, (ii) most radar experiments finding no effect focus on urban areas at relatively high altitude (see figure 6) where other effects such as orography are prone to confound the urban effect, and (iii) studies with radar data come later, at a time when methods have also evolved. To identify if the type of data precludes general conclusions, multi-city analyses based on transferable spatial comparisons using different data should be conducted.

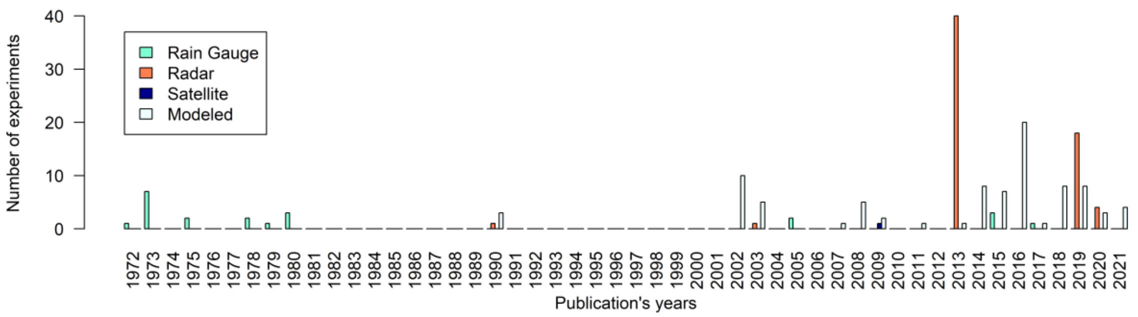

Figure 9. Data used by the experiments per year (all experiments).

- The urban effect seems to be occurring more in temperate climates than in continental climates for all seasons. Hopefully, as precipitation and climate data resources expand in new regions, additional experiments over other cities will be investigated and may provide new insights on the link between climate type and urban effect on the different types of precipitation such as convective or stratiform.

- The proxies used for geographical settings, the altitude, and the distance to the coast, are identified in our study to influence the experiment's conclusions. This confirms the observation of Yue et al. (2021) that the urban effect is complex and differs across cities that are located in different geographical contexts.

- The population does not influence the experiments' main conclusions on the effect of urban areas on precipitation, either because the size of the city has only a marginal influence on the urban effect, or because, in this study, we only focused on qualitative assessments. To conclude on this point, quantitative effects should be compared between experiments but as discussed in Section 3, it is quite difficult to compare quantitatively the effects between experiments due to the different methodological choices by the authors to measure the urban effect on precipitation.

- We did not find significant differences based on the data length, in other words, between case studies and climatological studies. Still, Liu & Niyogi (2019) in their meta-analysis identified a significant lack of agreement between these two types of studies. We suggested two reasons for these opposite results between our studies, the first one is that we studied the qualitative effect while Liu & Niyogi

(2019) studied the quantitative effect, and the second one is a different selection of experiments (16 articles in common for the analysis of 48 articles in both analysis).

- The original procedure used throughout this article can be reproduced for other research subjects. This methodology is split into two parts. The first is the selection of articles and the classification of variables and characteristics, which requires scientific expertise on the subject. The second part is the analysis using machine learning, which brings new information on the non-consensual state of the art of the subject.

As already stressed by Liu & Niyogi (2019), authors need to explicitly state the data that they use and the spatial or temporal comparisons that they do. Reading almost 500 papers, they found that only 10% provided quantitative information usable for their meta-analysis. We came across the same problem, many articles selected at the first stage were excluded due to a lack of explicit descriptions of data types and methodological choices.

Also, as the initial question asked 50 years ago “Do urban areas modify precipitation?” is evolving in “How do urban areas modify precipitation?”, authors need to state what urban characteristics they are focusing on, and what type of precipitative events they select for their experiments. Yue et al. (2021) encouraged such practices and investigations on the respective roles of the city barrier and city friction in the same weather process. Still, these reviews acknowledge that the effect of urban areas on precipitation is complex and differs between cities with different characteristics and geographical settings. In this study, we did find that climate and geographical settings play a role in the urban effect on precipitation. The next step that we support is the analysis of many cities with homogeneous datasets and quantification methods. With a reproducible spatial comparison for a large set of different cities, the urban effects could thus be attributed to urban characteristics and geographical settings. Numerical models are valuable tools to investigate the impact of specific urban characteristics on precipitation and allow to focus on specific precipitation events, such as convective precipitation. High-resolution climate models (grid cells under 3 km) are now widely available and can trustworthily represent these processes (e.g. Ban et al., 2021).

Acknowledgments:

This research is part of the Ph.D. project of Morgane Lalonde-Le Pajolec, funded by the EUR IPSL CGS. We thank the anonymous reviewers for their relevant suggestions.

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