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Time-series Analysis of Clusters in City Size Distributions

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Summary. Complex systems, such as urban systems, emerge unpredictably without the influence of central control as a result of adaptive behaviour by their component, interacting agents. This paper analyses city size distributions, by decade, from the south-western region of the United States for the years 1890–1990. It determines if the distributions were clustered and documents changes in the pattern of clusters over time. Clusters were determined utilising a kernel density estimator and cluster analysis. The data were clustered as determined by both methods. The analyses identified 4–7 clusters of cities in each of the decades analysed. Cities cluster into size classes, suggesting variability in growth rates at different scales.

1. Introduction

Complex systems are self-organised; interactions between variables at different scales are not regulated by a central controller (Bak *et al.*, 1988; Loreto *et al.*, 1995; Bonabeau, 1998). Rather, complex systems organise and manifest pattern in a decentralised manner via interactions between agents, variables and the system itself (Bonabeau, 1998). Self-organised systems are characterised by the ability of the system to adapt, which leads to broad-scale responses within the system (Krugman, 1996).

An urban system (i.e. a city) is a manifestation of human adaptation to the natural environment (Bessey, 2002). Urban systems exhibit spatial patchiness in their social and economic infrastructure (Grimm *et al.*, 2000). For example, the spatial heterogeneity of urban systems is typically established and maintained by government (for example, zoning regulations enforced by zoning boards and courts) and influenced on a different scale by other institutions such as businesses and community associations (Grimm *et al.*, 2000). As social animals, humans create institutions to regulate knowledge associated with large learning capacities (Pickett *et al.*, 1997). The institutions that govern human population density and location, and those populations themselves, are subject to change through time (Pickett *et al.*, 1997). For example, a variable that has an effect at a local level, such as movement of businesses or national policy, may have derived from a different scale (Dow, 2000).

Bessey (2002) suggested that functional processes act as corollaries of the ‘slaving principle’, in which large, slow processes

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(for example, national economies) enslave small, fast processes (for example, regional and city economies). There is evidence that suggests that pattern is a function of process in complex systems (Solé and Manrubia, 1995). Support for the proposition that local interactions can produce global structure via non-equilibrium phase transitions originally came from research on physical systems (Batten, 2001). Phase transitions can transform simple socioeconomic systems into complex ones and these transitions are highly sensitive to the spatial scale of the interactions between the agents involved (Batten, 2001). Spatial scales can change abruptly from local to global; inherently a non-linear process. In order to understand pattern and structure in urban systems, the non-linear character of interactions between agents at different scales must be elucidated (Batten, 2001). The first step in that process is characterising pattern in urban systems. The signature these interactions impart on the landscape (for example, cities and their size and distribution) may illuminate the nature of these processes upon complex systems (for example, urban systems) (Bessey, 2002). For example, urban primacy and modality in regional city size distributions suggest spatial and temporal discontinuity in urban systems (Bessey, 2002).

Importantly, much as Holling (1992) has suggested for ecosystems, the physical structure of the environment plays a crucial role in shaping the landscape of an urban system (Dow, 2000). For example, canals, railways and roads partly structure the flow of commerce and people in and out of cities. Variables such as wealth, education, status, property and power, which are distributed inequitably, are expressed at different spatial and temporal scales, and add to the hierarchical structuring of urban systems (Pickett *et al.*, 2001). For example, persons of wealth will locate their neighbourhoods at higher elevations, which reflects historical patterns of belief about health and disease (Meyer, 1994; Dow, 2000). The spatial heterogeneity in urban systems is affected by the generation, flow and concentration of resources (Pickett *et al.*, 1997).

Much of urban theory has developed from central place theory. A central place is characterised as an attractor which can have a number of small towns at equal distances from it, where the smaller towns make use of the central places' shops and services (Christaller, 1933). Christaller (1933) theorised that the differences in central places and their satellites produced two rules: the larger the central place, the less central places there are; and, the larger the central place, the greater the 'sphere of influence' of that place. Zipf (1949) identified a linear relationship for cities and characterised it as a reflection of national and political unity driven by a causal central place element. This distribution manifests when all central places in an urban hierarchy have the same average growth rates (Gibrat, 1957). Gabaix (1999a) states that Zipf's law for cities is an empirical fact in economics and for the social sciences in general. Zipf's law predicts that city size distributions will have a continuous distribution and conform to the restraints of a linear power law (Gabaix and Ioannides, 2004). If an urban system develops under these power laws, the resulting steady-state distribution of city sizes will approximate a rank–size distribution (Simon, 1955). Supporters of the proposition that urban distributions conform to Zipf's law believe that this fractal scaling distribution describes urban systems that are structured by a hierarchy of time-minimising spatial constraints (Zipf, 1949). This rank–size relationship for urban systems, as described by Zipf's law, is believed to be a reflection of a steady-state condition (Gabaix, 1999a). Thus, the assumption is that city sizes of a certain range will have similar growth processes (Gibrat's law) regardless of the particulars driving the growth of cities and that the distribution of these cities will conform to Zipf's law (Gibrat, 1957; Gabaix, 1999a).

City sizes are thought to conform to a power law (Zipf's law) due to the invariance of growth processes at the range of possible scales (Gabaix, 1999a). However, urban systems are not deterministic. Rather, they are entrained by stochastic, historical and hierarchical influences that make their development different from predictions based on physical laws (Pickett *et al.*, 2001). Further, city sizes are defined by the maximum potential welfare of the participants in the economy and these participants operate at different scales (Henderson, 1974; Kline *et al.*, 2001). Gabaix (1999a) has intimated that there are scale-specific processes at work on city size, when he states that above a certain city size, shocks (such as policy or natural disasters) stop declining with the size of the cities in question. Additionally, Lynch (1960) identified five spatial scales for urban systems, including: district, edge, path, node and landmark. These spatial scales manifest as neighbourhoods, commercial–residential divides and transport corridors (Dow, 2000). Gabaix (1999a) contends that, even if two cities in the rank order are quite close in size, it does not disprove Zipf's law. However, deviations from Zipf's law may provide an additional source of information about the state of the system and a starting-point in the search for explanations for such deviations (Dziewonski, 1972). Gabaix (1999a) has indicated that, if city sizes are indeed structured by non-linear processes operating at different scales, then a power law probably does not capture the actual structure in urban systems.

Bessey (2002) has found that bimodality and polymodality are defining features of US urban systems at national and regional scales. Bessey utilised rank–size and constant Gini models to analyse national and regional city size data. These models revealed departures from the Zipf prediction and increased population concentration in the largest cities (i.e. upper tail of the city size distribution) in each region. At a finer scale, individual cities often followed paths that were sharply discontinuous in their growth trajectories. For individual cities, Bessey found that there were periods of static behaviour linked by periods of oscillatory turbulence or instability, constrained by regional and national processes. Additionally, at a regional level, Bessey identified that the tenure of some cities within a particular mode was sometimes highly transient.

Cities are the by-product of conflict between deglomerative diseconomies of scale and agglomeration forces (Rosser, 1991). The interplay between these forces manifests in bifurcations, which in turn lead to discontinuous leaps in population (Rosser, 1991). The interaction between these processes across scales is fundamentally non-linear and could manifest in cities clustering into size classes (Rosser, 1991). If this is so, we expect persistent, variable clusters of cities, as opposed to a continuous distribution of cities, despite the normal dynamics of the system. Building upon Bessey (2002), we test these predictions with empirical datasets that reflect system structure over time.

2. Methods

We define an urban system as a human settlement above a threshold population size that satisfies the functional requirements of that population (Bessey, 2002). The cut-off for determining what is urban is arbitrary and arises from practical rather than theoretical considerations (Marshall, 1989). This analysis used a US census dataset incorporating the urbanised area (UA) definition. A UA comprises a central place and the urban fringe, which includes other 'places' (Bessey, 2000). The Bureau of the Census officially defines a 'place' as a concentration of population, which must have a name and be locally recognised, although it may or may not be legally incorporated under the laws of its state (Bessey, 2002).

Many Bureau of the Census classifications have evolved through several definitional changes over the past 120 years. Regional systems theory conceives of cities as the central places in regional, social and economic systems, nested within a larger hierarchy of cities and regions (Skinner and Henderson, 1999). Bureau of Economic Analysis (BEA) regions comprise defined entities whose boundaries hold historically. Additionally, aggregating cities at the national scale masks discontinuous pattern that manifests at a regional scale

(Skinner and Henderson, 1999). Analysing the data based on BEA regions allowed for investigations of pattern along smaller and more uniform biophysical, economic and sociocultural characteristics (Bessey, 2002).

We ranked cities in order of population size to determine whether clusters existed within the city size distribution. This study used a BEA dataset of cities in the south-western region (Arizona, New Mexico, Oklahoma and Texas) of the US. City size distributions were analysed with simulations that compared actual data with a null distribution established by calculating a kernel density estimate of the log-transformed data (Hall and York, 2001). Significance of clusters in the data was determined by calculating the probability that the observed discontinuities were chance events by comparing observed values with the output of 1000 simulations from the null set (Restrepo *et al.*, 1997). Because *n* in our 11 datasets varied from 48 cities in 1890 to 161 cities in 1990, we maintained a constant statistical power of ~0.50 for detecting discontinuities (Lipsey, 1990). Maintaining constant power rather than constant alpha levels (i.e. keeping Type II error rates constant rather than Type I error rates) is a more robust approach when the focus is the detection and comparison of pattern among datasets with greatly varying *n* (Holling and Allen, 2002). We confirmed our results with cluster analysis based on variance reduction (SAS Institute Inc., 1999). A discontinuity was defined as an area between successive city sizes that significantly exceeded the differences between adjacent city sizes generated by the continuous null distribution (Allen *et al.*, 1999). A cluster was a grouping of three or more cities with populations not exceeding the expectation of the null distribution (Allen *et al.*, 1999). City size clusters were defined by the two end-point cities that defined either the upper or the lower extremes of the cluster (Allen *et al.*, 1999).

3. Results

There were 48 cities in 1890 and 161 cities in 1990 (Table 1). Within decades, city sizes ranged from 2541 to 38 067 in 1890, to 10 030 to 3 198 259 in 1990. Beginning in 1890, the largest city in the south-western region of the US was Dallas (Table 1). For the next three decades (1900–20), San Antonio was the largest city in the region and then Houston from 1930 to 1970 (Table 1). Finally, from 1980 to 1990, Dallas–Fort Worth reascended to the largest city in the region, after Dallas and Fort Worth merged into one urbanised region (Table 1). These three cities represent the dominant cities of this region and they jockeyed for position over the course of the past century (Table 2).

City size distributions for the south-western region of the US were discontinuous. Distinct clusters of cities were identified in each decade, by all methods of analysis. We observed 4–7 clusters in each decadal dataset (Table 1). This structure is significant, as random draws of the same *n* from the null model revealed that 91 per cent of the outputs randomly generated were either unimodal or bimodal in their distribution, and fewer than 1 per cent had over 4 discontinuities (Allen *et al.*, 1999). For each time-period analysed, there is a range of city sizes, a different number of cities represented and a different hierarchical relationship of the cities, yet the underlying structure remains discontinuous.

Discontinuities are persistent throughout the 20th Century in the south-western region of the US (Figure 1). From 1890 until 1920, the cities in the region are spread fairly evenly based on their size (Figure 1). Beginning in 1930, a consistent trend develops that continues until 1990; there are an increasing proportion of smaller cities in the lower tail of the city size distributions and a persistent trend of few very large cities in the upper tail of the city size distributions (Table 3).

It is illuminating to track the movement of Galveston, Houston and Phoenix, in particular, to demonstrate change over time in the rank of cities. In 1890, Galveston (29 084) and Houston (27 557) had comparable populations and were members of the second-largest cluster of cities. Phoenix (3152), however, was a small town and a member of a large

Table 1. Largest city, maximum city size, number of clusters and number of cities for the south-western region of the US

Year	Largest city	Largest city population	Number of clusters	Number of cities
1890	Dallas	38 067	6	48
1900	San Antonio	54 000	7	54
1910	San Antonio	99 000	6	53
1920	San Antonio	168 700	5	55
1930	Houston	295 700	6	73
1940	Houston	416 100	5	69
1950	Houston	701 600	5	94
1960	Houston	1 140 000	5	120
1970	Houston	1 677 863	4	123
1980	Dallas–Fort Worth	2 451 390	4	149
1990	Dallas–Fort Worth	3 198 259	6	161

cluster with numerous cities of similar small size. By 1900, Houston ascended to the top cluster, while Galveston descended from the third-ranked city in 1890 to the seventh-ranked city in 1910. This trend continued, as Galveston continued a slow slide until it settled into a mid-range cluster by 1990 with a population of 58 263. By 1900, Phoenix had moved into a mid-range cluster with a population of 5544 and it moved slightly up in 1910 with a population of 11 134. By 1930, Phoenix had grown to 67 100 people and was the eighth-largest city in the region, surpassing Galveston. By 1960, Phoenix was the fourth-largest city in the region with a population of 552 043. By 1970, Phoenix ascended to the third-largest city in the region, where it remained as of 1990, with a population of 2 006 239.

4. Discussion

The results of this analysis demonstrate that the structure of urban systems is discontinuous, as theorised by Bessey (2002). While membership of a city in a particular cluster of cities may change over time, these changes do not alter the persistent nature of discontinuities in the city size distributions of this region. Further, changes in cluster membership do not result in continuous distributions. For example, in 1890, Dallas was the largest city in the region, with Galveston and Houston as two of its rival cities within the same cluster. Phoenix, on the other hand, was a small town in 1890, with no indication of its meteoric rise over the course of the next century. During the next few decades, Houston cemented its position of dominance in the region, Galveston began a slow slide to become a medium-sized city and Phoenix ascended to the third-largest city in the region by 1990. These cities demonstrate that change drives urban systems on a city level, but the underlying discontinuities in the size distributions persist.

Gabaix (1999b) has observed that explanations for Zipf's law have revolved around two explanations: one economic and one defined by random processes. Gabaix is critical of an economic explanation for Zipf's law, as he observed that it is difficult to conceive of vastly different economies (for example, US 1991 vs India 1911) producing the same balance of forces that could produce Zipf's law. While Zipf's law is stated as an empirical fact, there are frequent departures from the distribution. For instance, Rosen and Resnick (1980) describe a more even city size distribution for the US than would be predicted by Zipf's law, while Black and Henderson (2003) demonstrated that the US city size distribution was more concentrated than predicted by Zipf's law. In reality, the rank–size rule is rarely obtained (Guerin-Pace, 1995), as the non-constancy of the estimating coefficient (q) over time suggests that city growth rates are not

Table 2. Cities in the cluster at the upper tail (i.e. largest cities) of the distribution by decade for the south-western region of the US

Year	City
1890	Dallas
	San Antonio
	Galveston
	Houston
	Fort Worth
	Austin
	Waco
1900	San Antonio
	Houston
	Dallas
	Galveston
1910	San Antonio
	Dallas
	Houston
	Fort Worth
	Oklahoma City, OK
1920	San Antonio
	Dallas
	Houston
	Fort Worth
	Oklahoma City, OK
	El Paso
	Tulsa, OK
1930	Houston
	Dallas
	San Antonio
1940	Houston
	Dallas
	San Antonio
1950	Houston
	Dallas
	San Antonio
1960	Houston
	Dallas
	San Antonio
	Phoenix, AZ
	Fort Worth
	Oklahoma City, OK
1970	Houston
	Dallas
	Phoenix, AZ
	San Antonio
	Fort Worth
	Oklahoma City, OK
1980	Dallas–Fort Worth
	Houston
	Phoenix, AZ
	San Antonio
	Oklahoma City, OK
1990	Dallas–Fort Worth
	Houston
	Phoenix, AZ
	San Antonio
	Oklahoma City, OK

proportional (Brakman *et al.*, 2001). Brakman *et al.* (2001) are critical of Gabaix's use of Gibrat's law to characterise city size distributions, because Gabaix's explanation entails that, for each city in a distribution, agglomeration forces negate spreading forces. This assumes homogeneity in underlying growth processes—i.e. growth is independent of city size—which appears inconsistent with the empirical data, particularly in light of the detection of deviations from Zipf's law in this dataset (i.e. the south-western region of the US) (Bessey, 2002).

Initial conditions (geophysical and economic) can loom large in competitive city growth processes (Bessey, 2002). Dendrinos (1992) describes the existence of a relative, per capita, product developmental threshold below which urban wealth variations over time are almost negligible. A city's relative population share and wealth appear to depend heavily on its past and current location relative to this threshold (Bessey, 2002). Temporally discrete urban growth rates (Papageorgiou, 1980) and clumping in the spatial ranges of city functions (Korcelli, 1977) provide clues into how spatially large systems (i.e. national economies) entrain (Holling, 1992) spatially smaller units, including regional and city economies, to produce stability in macrostructure but great diversity in the available growth paths (Dendrinos and Sonis, 1990).

Bessey (2002) has theorised that the spacing of cities on a national scale is driven by a slow dynamic. The landscape provides locations, such as valleys or natural harbours, which favour agglomeration (Brakman *et al.*, 2001). Human-ecological systems (such as cities) self-organise and the manifestation of size (population) reflects the limitations of the landscape (Berkes and Folke, 1998). For example, the rise of a city like Phoenix, Arizona, may have been the result of a vacuum of urbanisation in the south-western region of the US, combined with access to a critical resource (such as water) for city growth and development. At a regional scale, a fast variable driven by the minimum population and income needed for city survival also influences city size (Bessey, 2002).

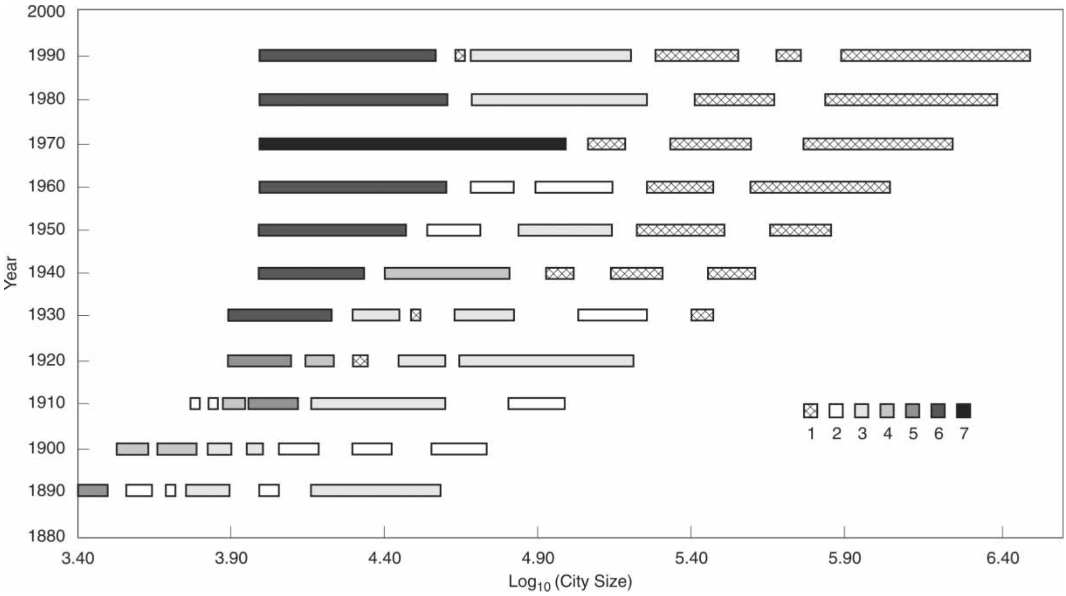

Figure 1. Discontinuities in the city size distributions for the south-western region of the US from 1890 to 1990. *Notes*: Bars represent cities within a size class and are separated from the adjacent size class by a significant discontinuity; the different shades indicate the percentage of cities within a cluster: (1) 0–5 per cent; (2) 5–10 per cent; (3) 10–20 per cent; (4) 20–40 per cent; (5) 40–60 per cent; (6) 60–80 per cent and (7) 80–100 per cent.

Reed (2002) argues that the rank–size distribution of cities is best explained mathematically as a consequence of stochastic processes. However, geographical and economic factors are likely to be important in the growth and size of cities, and it is the aggregation of these variables that manifests in the distribution of city sizes. As Reed (2002) has observed, the difficulty in characterising the observed pattern of city sizes is largely specifying stochastic models that can describe the distributions. It is unlikely that there is a single, general theory that can explain all instances of power law behaviour (Reed, 2001).

Table 3. Number of cities, number of clusters and the number of cities within clusters by decade for the south-western region of the US

Year	Number of cities	Number of clusters	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
1890	48	6	21	5	3	9	3	7	N/A
1900	54	7	17	13	8	6	3	3	4
1910	53	6	5	3	11	21	8	5	N/A
1920	55	5	26	12	3	7	7	N/A	N/A
1930	73	6	46	9	3	8	4	3	N/A
1940	69	5	43	17	3	3	3	N/A	N/A
1950	94	5	66	9	11	5	3	N/A	N/A
1960	120	5	90	9	9	6	6	N/A	N/A
1970	123	4	106	5	6	6	N/A	N/A	N/A
1980	149	4	108	30	6	5	N/A	N/A	N/A
1990	161	6	118	3	28	3	5	5	N/A

Note: City sizes are broken into clusters (i.e. size classes) from smallest (cluster 1) to largest (cluster 7) separated by significant discontinuities.

Certainly then, it will take time to develop a theory to characterise clustering in city size distributions.

Increasing returns issues in economics are dynamic processes with random events, and positive and negative feedbacks; in short, non-linear stochastic processes (Arthur, 1999). Goldenfeld and Kadanoff (1999) refer to non-linear change in complex systems as intermittency. Intermittency is exemplified by significant changes in the dynamics of a system, which manifest in identifiable patterns. Cities grow with periods of rapid growth, interspersed with periods of little growth or stasis and, in some cases, decline (Reed, 2002). We speculate that this intermittent non-linear change manifests in a clustered city size distribution in the south-western region of the US.

Building upon the detection of departures from Zipf's law for this regional dataset (Bessey, 2002), this analysis identifies clustering in city size distributions for the south-western region of the US. There are persistent discontinuities in city size distributions throughout the 20th century, despite consistent change in the membership of individual clusters and major population movements to the south-western US during this period. Our analysis indicates that there is important pattern in regional urban system distributions that has been ignored in the desire to fit city size distributions to the broad strokes of power laws, when the structure and pattern of these systems are more dynamic than recent research on scaling in city size distributions has indicated. This research supports the findings of Bessey (2002) as it is apparent that, despite differing developmental histories, regional urban systems in the south-western US concentrate population in the region's largest cities. This pattern is manifested in a discontinuous structure in the city size distributions of the decadal datasets.

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