

1 **Cities of the future, visualizing climate change to inspire actions**

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12 **Abstract**

13 Combating against climate change requires unified action across all sectors of
14 society. However, this collective action is precluded by the ‘consensus gap’ between
15 scientific knowledge and public opinion. A growing body of evidence suggests that
16 facts do not persuade people to act. Instead, it is visualization - the ability to simulate
17 relatable scenarios - is the most effective approach for motivating behavior change.
18 Here, we exemplify this approach, using current climate projections to enable people
19 to visualize cities of the future, rather than describing intangible climate variables.
20 Analyzing city pairs for 520 major cities of the world, we characterize which cities will
21 most closely resemble the climate conditions of which other major cities by 2050. On
22 average, most cities will resemble cities that are over 1000km south, and 22% of
23 cities will experience climate conditions that are not currently experienced by any
24 existing major cities. We predict that London’s climate in 2050 will resemble
25 Barcelona’s climate today, Madrid will resemble to Marrakesh, Moscow to
26 Sofia, Seattle to San Francisco, Stockholm to Budapest, Tokyo to Changsha, etc.

27 Our approach illustrates how complex climate data can be packaged to provide
28 tangible information. By allowing people to visualize their own climate futures, we
29 hope to empower citizens, policy makers and scientists to visualize expected climate
30 impacts and adapt decision making accordingly.

31 **Main text**

32 Climate change is a systemic threat to humankind ¹. In 1992, 172 nations convened in Rio de
33 Janeiro to establish the United Nations Framework Convention on Climate Change
34 (UNFCCC), recognizing the urgent need for climate action. Yet, 26 years later, we still have
35 to alter the course of this global threat ². The UN estimates that the cost of climate change
36 under a business as usual scenario will exceed \$12 trillion by 2050 ³. Less than 0.1% of this
37 amount has been committed to the UNFCCC's Green Climate Fund to incentivize global
38 climate action ⁴. Despite the overwhelming scientific consensus that human activity is driving
39 climate change ^{1,5}, 53% of people in the world still do not believe that climate change will
40 affect them during their lifetime ⁶.

41

42 The gap between scientific and public understanding (referred to as the Consensus Gap) is
43 largely attributed to failures in climate change communication ⁷. Often limited to ad-hoc
44 reporting of extreme weather events or intangible, long-term climate impacts (e.g. changes in
45 average temperature by 2100). The intangible nature of this reporting fails to adequately
46 convey the urgency of this issue to a public audience on a consistent basis ⁸. It is hard for
47 most people to envision how an additional 2°C of warming might affect daily life. This
48 ineffective communication of climate change facts, compounded by the uncertainty about the
49 extent of expected changes, has left the door open for widespread misinterpretation about
50 the existence of this unassailable global phenomenon.

51

52 History has repeatedly shown us that data and facts alone do not inspire humans to change
53 their beliefs or act ⁸. Increased scientific literacy has no correlation with the acceptance of

54 climate change facts ⁹, and can instead have an opposite effect. A growing body of research
55 demonstrates that visualization - the ability to create a mental image of the problem - is the
56 most effective approach for motivating behavior change ^{10,11}. The greatest challenge facing
57 climate scientists is no longer the detailed characterization of future climate, but the
58 development of communication mechanisms that inspire coordinated action. We argue that
59 enabling people to visualize a tangible climate future is the most crucial objective facing
60 current climate science.

61

62 Here, we implement this strategy, taking the current climate data for the world's major cities
63 (Current Cities), and projecting what they will be like in 2050 (Future Cities). Rather than
64 describing the quantitative changes in climate variables, we quantify which Current Cities will
65 most closely resemble the climate conditions of Future Cities (see Material and Methods).
66 For example, using our approach we can predict that London's climate in 2050 will resemble
67 Barcelona's climate today. Our approach makes the intangible (e.g. a given rise in
68 temperature) tangible, in terms of people's current experience. This is intended to capture
69 people's imagination, not only because over 68% of the world's population will live urban
70 areas ¹², but also because iconic locations allow us to visualize the imminent changes that
71 are likely to occur within our lifetimes.

72

73 We characterized the climate of the world's 520 major cities using 19 climatic variables that
74 reflect the variability in temperature and precipitation regimes for current and future
75 conditions. Future conditions are estimated using a realistic Representative Concentration
76 Pathway (RCP4.5), which considers a stabilization of CO₂ emissions by mid-century (see
77 Material and Methods). Using a multivariate analysis, we analyzed the climate similarity of all
78 Current and Future cities to one another (Figure 1, Database S1). This simple analysis
79 enable us to estimate which major cities of the world will remain relatively similar, and which
80 will shift to reflect the climate of another city by 2050. Overall, our analysis shows that 77% of
81 the world's Current Cities will experience a striking change in climate conditions, making

82 them more similar to the conditions of another existing city (see Databases S1-S2). In
83 addition, 22% of cities will experience climate conditions that are unlike any major city
84 currently existing on the planet (Figure 2a-b).

85

86 The proportion of shifting cities varied consistently across the world. Cities in northern
87 latitudes will experience the most dramatic shifts in extreme temperature conditions (Figure
88 2c-d). For example, across Europe, both summers and winters will get warmer, with average
89 increases of 3.5°C and 4.7°C, respectively. These changes would be equivalent to a city
90 shifting 1,000 km further south, under current climate conditions (Figure 2c-d). Consequently,
91 by 2050, striking changes will be observed across the northern hemisphere: London's
92 climate in 2050 will be more similar to the current climate in Barcelona than to London's
93 climate today; Stockholm will be more similar to Vienna; Moscow to Sofia; Portland to San
94 Antonio, San Francisco to Lisbon and Tokyo to Changsha; (Figure 1, Database S2).

95

96 Cities in the tropical regions will experience smaller changes in average temperature, relative
97 to the higher latitudes. However, shifts in rainfall regimes will dominate the tropical cities.
98 This is characterized by both increases in extreme precipitation events (+5% rainfall wettest
99 month) and, the severity and intensity of droughts (-14% rainfall driest month). With more
100 severe droughts, tropical cities will move slightly away from the equator, towards drier
101 climates (Figure 2c-d). However, the fate of major tropical cities remains highly uncertain
102 because many tropical regions will experience unprecedented climate conditions.
103 Specifically, of all 22% of cities that will experience novel climate conditions, most (64%) are
104 located in the tropics. These include Manaus, Libreville, Kuala Lumpur, Jakarta, Rangoon,
105 and Singapore (Figure 2a-b, Database S2).

106

107 Our analysis allows us to visualize a tangible climate future of the world's major cities. These
108 results enable decision makers from all sectors of society, to envision changes that are likely
109 to occur in their own city, within their own lifetime. Londoners, for example, can start to

110 consider how their 2050 equivalents (e.g. Barcelona today) have taken action to combat their
111 own environmental challenges. In 2008, Barcelona experienced extreme drought conditions
112 which required the importation of €22m of drinking water. Since then, the municipal
113 government has implemented a series of 'smart initiatives' to manage the city's water
114 resources (including the control of park irrigation and water fountain levels). The Mayor of
115 London has factored drought considerations into his Environment Strategy aims for 2050 ¹³,
116 but this study can provide the context to facilitate the development of more targeted climate
117 strategies. In addition, this information can also empower local citizens to evaluate proposed
118 environmental policies. By allowing people to visualize their own climate futures, we hope
119 that this information can engage people to take action, both to mitigate and adapt to climate
120 change.

121

122 Our study is not a novel model revealing updated climate projections or expectations by
123 2050. Instead, our analysis is intended to illustrate how complex climate data can be
124 effectively summarized into tangible information that can be easily interpreted by anyone. Of
125 course, the climate scenarios that we have used are based on predictions from a few climate
126 models, run under a single (business as usual) climate scenario. We recognize that these
127 models are characterized by huge amounts of uncertainty ¹⁴, and the predicted Future Cities
128 may change as these Earth System Models are refined, in particular in light of urban climate
129 specificities ¹⁵. However, our results are likely to reflect the qualitative direction of climate
130 changes within cities and so meet our primary goal, which is to communicate predicted
131 climate changes to a non-specialist audience in order to motivate action. When model
132 projections are updated, we would recommend communicating any new results with this goal
133 in mind.

134

135 Finally, our work is a call to encourage scientists to take more responsibility in the fight
136 against climate change. In addition to furthering current knowledge, we should improve our
137 communication in order to empower stakeholders and policy makers that are trying to

138 change the course of climate change. It is time to bridge the gap between knowledge and
139 action.

140 **Materials and Methods**

141 Major cities of the world

142 We selected the “major” cities of the world from the “LandScan (2016) High Resolution global
143 Population Data Set” created by the Oak Ridge National Laboratory¹⁶. By “major” cities, we
144 considered cities that are an administrative capital or that account more than 1,000,000
145 inhabitants. In total, 520 cities were selected.

146 The climate database

147 To characterize the current climate conditions among these major cities of the world, we
148 extracted 19 bioclimatic variables from the latest Worldclim global raster layers (Version 2;
149 period 1970-2000) at 30 arc-seconds resolution¹⁷. These variables captured various climatic
150 conditions, including yearly averages, seasonality metrics, and monthly extremes for both
151 precipitation and temperature at every location.

152 Future data: GCMs, downscaling and future scenarios

153 For the future projections, the same 19 bioclimatic variables were averaged from the outputs
154 of three general circulation models (GCM) commonly used in ecology^{18,19}. Two Community
155 Earth System Models (CESMs) were chosen as they investigate a diverse set of earth-
156 system interactions: the CESM1 BGC (a coupled carbon–climate model accounting for
157 carbon feedback from the land) and the CESM1 CAM5 (a community atmosphere model)¹⁸.
158 Additionally, the Earth System component of the Met Office Hadley Centre HadGEM2 model
159 family was used as the third and final model¹⁹. To generate the data, we chose
160 Representative Common Pathway 4.5 (RCP 4.5) scenario from the Coupled Model
161 Intercomparison Project Phase 5 (CMIP5) as the input. It is a stabilization scenario, meaning
162 that it accounts for a stabilization of radiative forcing before 2100, anticipating the
163 development of new technologies and strategies for reducing greenhouse gas emissions²⁰.

164 For each output, a delta downscaling method developed by the CGIAR Research Program
165 on Climate Change, Agriculture and Food Security (CCAFS) was applied to reach a
166 resolution of 30 arc-seconds²¹, using current conditions Worldclim 1.4 as a reference.

167 Summarizing the current climate among the major cities through a principal component
168 analysis

169 The 19 current and future bioclimatic variables were extracted from the coordinates of the
170 520 major cities (i.e., the city centroids), meaning each city had two sets of bioclimatic
171 metrics: the current climate data for the world's major cities (Current Cities) and the
172 equivalent 2050 projection (Future Cities) according to the average of the three RCP 4.5
173 GCMs.

174 A principal components analysis (PCA) was then performed on current bioclimatic data in
175 order to account for correlation between climate variables and to standardize their
176 contributions to the subsequent dissimilarity analysis²². As the first four principal components
177 accounted for more than 85% of the total variation of climate data (40.2%, 26.9%, 10.5% and
178 7.6%, respectively), the remaining principal components were dropped from later analyses.
179 The main contributing variables to the four components are the temperature seasonality (axis
180 1), the minimum temperature of the coldest month (axis 1), the maximum temperature of the
181 warmest month (axis 2), the precipitation seasonality (axis 2), the precipitation of the driest
182 (axis 4) and of the wettest (axis 3) month, and the temperature diurnal range (axis 4,
183 supplementary figure 1).

184 Analysis of changes between current and future cities from the PCA

185 The future climate of each city was then projected within these four principal components
186 (using the PCA eigenvectors derived from the bioclimatic variables of the current climate) to
187 allow for direct comparison between Current and Future Cities (supplementary figure 1a-b).
188 On the plane defined by the first two components of the PCA (supplementary figure 1a), we
189 observe changes towards less temperature seasonality, with higher maximal and minimal

190 temperatures during the year, as well as higher precipitation seasonality, with higher
191 precipitation in the wettest month but lower precipitation in the driest one. While no clear
192 trend can be observed along the third axis, the changes along the fourth axis show higher
193 temperature diurnal range (supplementary figure 1b), i.e. the daily difference between cities'
194 maximum and minimum temperatures will increase. In brief, cities of the world become
195 hotter, in particular during the winter and the summer. Wet seasons become wetter and dry
196 season drier.

197 Calculating the extent of the covered climate domain

198 For further interpretation of the results, a convex hull was computed from the coordinates of
199 the Current Cities within the multivariate space defined by the first four principal components
200 axes²³. For reference, a convex hull of a set of N-dimensional points forms the smallest
201 possible hypervolume (in N-dimensions) containing all points defined in that set; in this case,
202 it defines the bounds of climatic combinations that Earth currently experiences in these 520
203 cities. All Future Cities falling outside the hypervolume of this convex hull represent currently
204 non-existent bioclimatic assemblies in these cities. Overall 78% of the 520 Future Cities
205 present a climate within this hypervolume, while 22% of the Future Cities' climate conditions
206 (many of which are distributed around the equator and in arid or semi-arid regions) would
207 disappear from this current climatic domain (Figure 2).

208 Pairing cities based on the similarity between current and future climate conditions

209 Euclidean distances (i.e., dissimilarity indices) were calculated for every combination of
210 Current and Future City based on their coordinates within the multivariate space defined by
211 the first four principal components axes, creating a symmetric dissimilarity matrix with
212 pairwise comparisons for all cities (see Database S1). The Euclidean distance was
213 calculated using the vegan package on R²². Each Future City was then paired with its three
214 closest Current Cities based on the dissimilarity values (see Databases S1-2). Three cities
215 are kept for each Future city in order to facilitate comparison between Current and Future

216 climate, as all cities are not necessarily known by the reader. To avoid shifts due to pixel
217 mismatch between Current and Future climate conditions, the final analysis was performed
218 keeping shift values between the 5th and the 95th percentile, i.e. keeping 477 out of the
219 original 520 cities. Results show that 77% of the world's Current Cities will experience a
220 striking change in climate conditions, making them more similar to the conditions of another
221 currently existing city.

222 Calculating the standardized latitudinal shift

223 To illustrate and summarize the shifts between Current and Future Cities, we calculated the
224 importance of latitudinal shift between the most similar pairs. Shifts in latitude were
225 standardized for both hemisphere, so that a shift south in the northern hemisphere is equal to
226 a shift north in the southern hemisphere. In other words, the standardized latitudinal shift
227 illustrates a shift in relation to the equatorial line (shifting away from or towards the equator).
228 The results (Figure 2) show that cities in boreal and temperate regions tend to move towards
229 the equator while cities in tropical regions tend to move away from the equator.

230

231 Analyses and figures were performed using Rcran version 3.3.2, maps were built using Q-
232 GIS 3.0.

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- 283

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288 **Author Contributions**

289 J.-F.B. conceptualized the study and did the analyses. J.-F.B., E.C., T.E., S.H., J.H, I.H.,
290 H.M., S.M., G.M., J.M., L.M., D.R., K.Y., C.Z. and T.W.C. wrote of the manuscript.

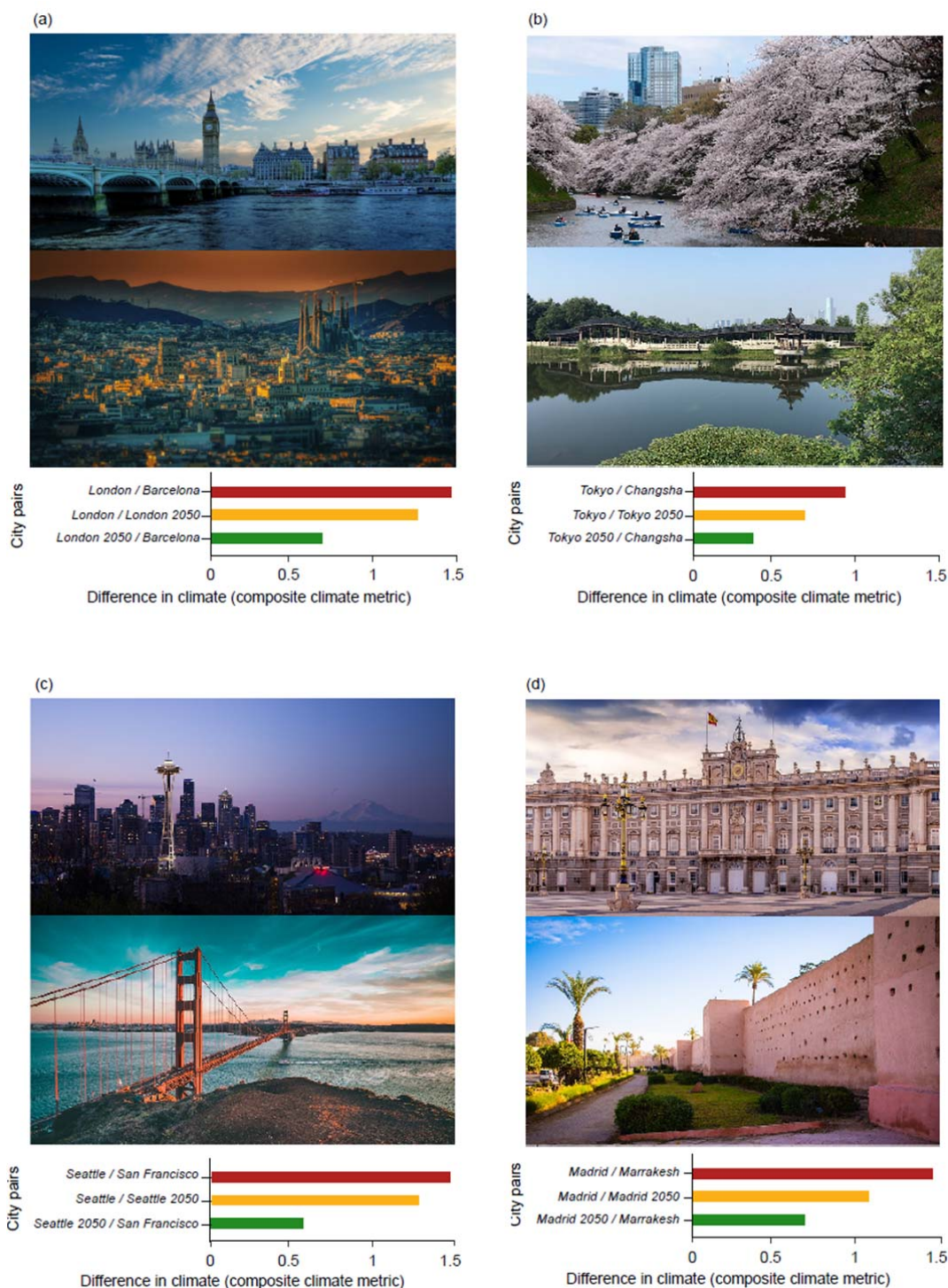
291 **Competing interests.**

292 The authors declare no competing interests.

293 **Material and Correspondance.**

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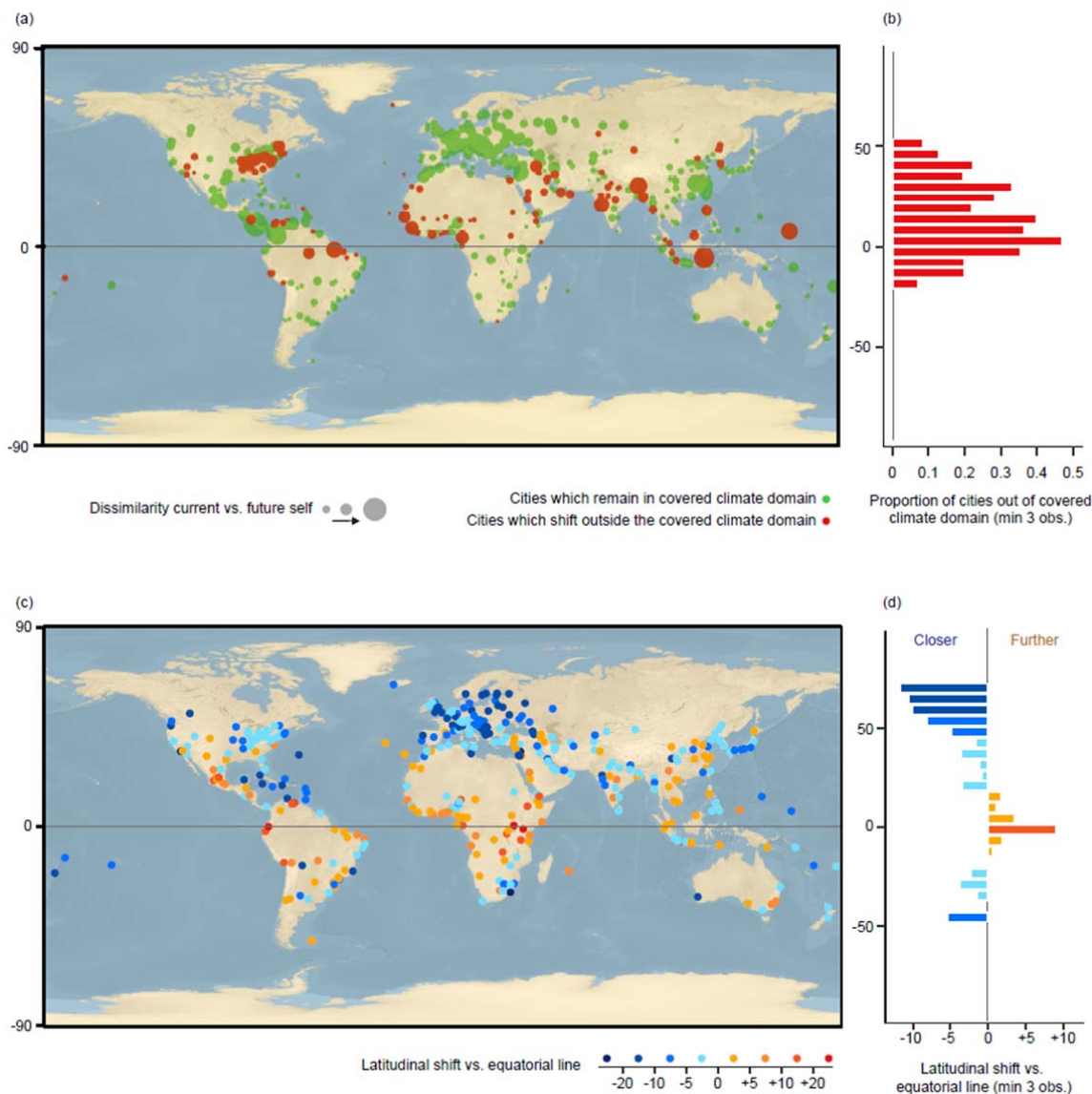
296 **Figures.**



297

298 **Figure 1| Future cities and similar current climate counterpart.** Difference between
 299 future and current climate for four cities and an example of their similar current counterpart.
 300 Illustration of the results of the analysis for London (**a**; counterpart: Barcelona), Buenos Aires
 301 (**b**; counterpart: Sidney), Nairobi (**c**; counterpart:Beirut) and Portland (**d**; counterpart:San
 302 Antonio). Images of Barcelona and London were obtained on Pixabay, shared under
 303 common creative CC0 license.
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Figure 2| Extent of climate changes in major cities of the world by 2050. a, b, the extent of change in climate conditions. Cities predicted to have climates that no major city has experienced before are colored in red (mostly within the tropics). Cities for which future climate conditions reflect current conditions in other major cities of the world are shown in green. The size of the dots represents the magnitude of change between current and future climate conditions. **b,** The proportion of cities shifting away from the covered climate domain (concentrated in the tropics). **c,d,** The extent of latitudinal shifts in relation to the equatorial line. Cities shifting towards the equator are colored with a blue gradient (mostly outside the tropics), while cities shifting away from the equator are colored with a yellow to red gradient (mostly within the tropics). **d,** A summary of the shift by latitude is illustrated in a barchart, with shifts averaged by bins of 5 degrees

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