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

2   Jean-Francois Bastin[1*], Emily Clark[1], Thomas Elliott[1], Simon Hart[2], Johan van den Hoogen[1],

3   Iris Hordijk[1], Haozhi Ma[1], Sabiha Majumder[1], Gabriele Manoli[3], Julia Maschler[1], Lidong Mo[1],

4   Devin Routh[1], Kailiang Yu[1], Constantin Zohner[1] and Thomas, W. Crowther[1]

5   1. Crowther Lab, Department of Environmental Systems Science, Institute of Integrative

6   Biology, ETH Zürich, Zürich, Switzerland

7   2. Plant Ecology, Department of Environmental Systems Science, Institute of Integrative

8   Biology, ETH Zürich, Zürich, Switzerland

9   3. Department of Civil, Environmental and Geomatic Engineering, Institute of Environmental

10   Engineering, ETH Zürich, Zürich, Switzerland

11   *corresponding author (bastin.jf@gmail.com)

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 CO_2 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 Laboratory[16]. 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 resolution[17]. 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 model[19]. 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 emissions[20].

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-seconds[21], using current conditions Worldclim 1.4 as a reference.

167   <u>Summarizing the current climate among the major cities through a principal component</u>

168   <u>analysis</u>

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 analysis[22]. 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   <u>Analysis of changes between current and future cities from the PCA</u>

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 <u>Calculating the extent of the covered climate domain</u>

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 axes[23]. 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 <u>Pairing cities based on the similarity between current and future climate conditions</u>

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 R [22]. 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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284 **Acknowledgments**

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.**

294 Correspondence and material requests should be addressed to Jean-Francois Bastin

295 (bastin.jf@gmail.com)
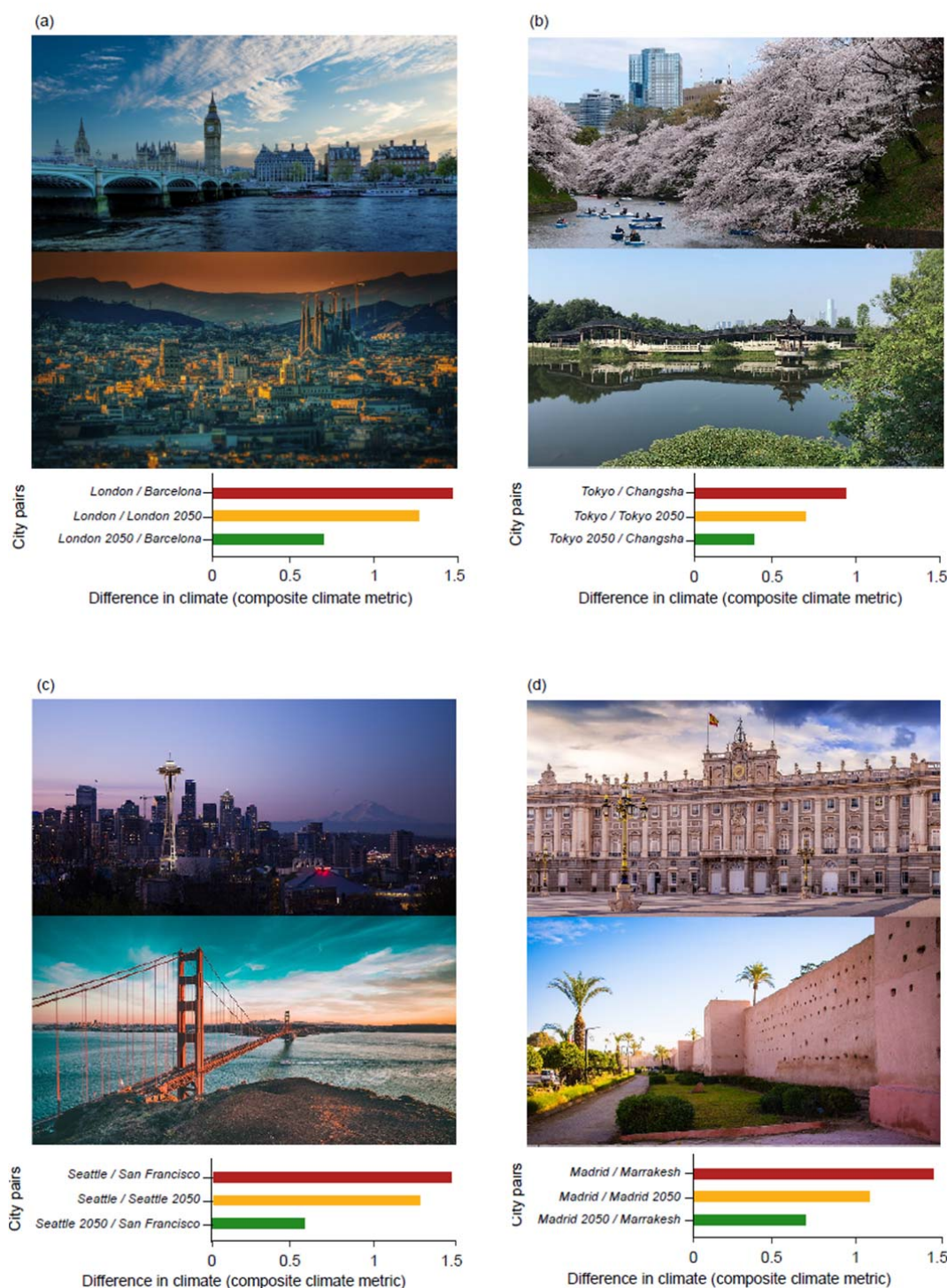
296 **Figures.**

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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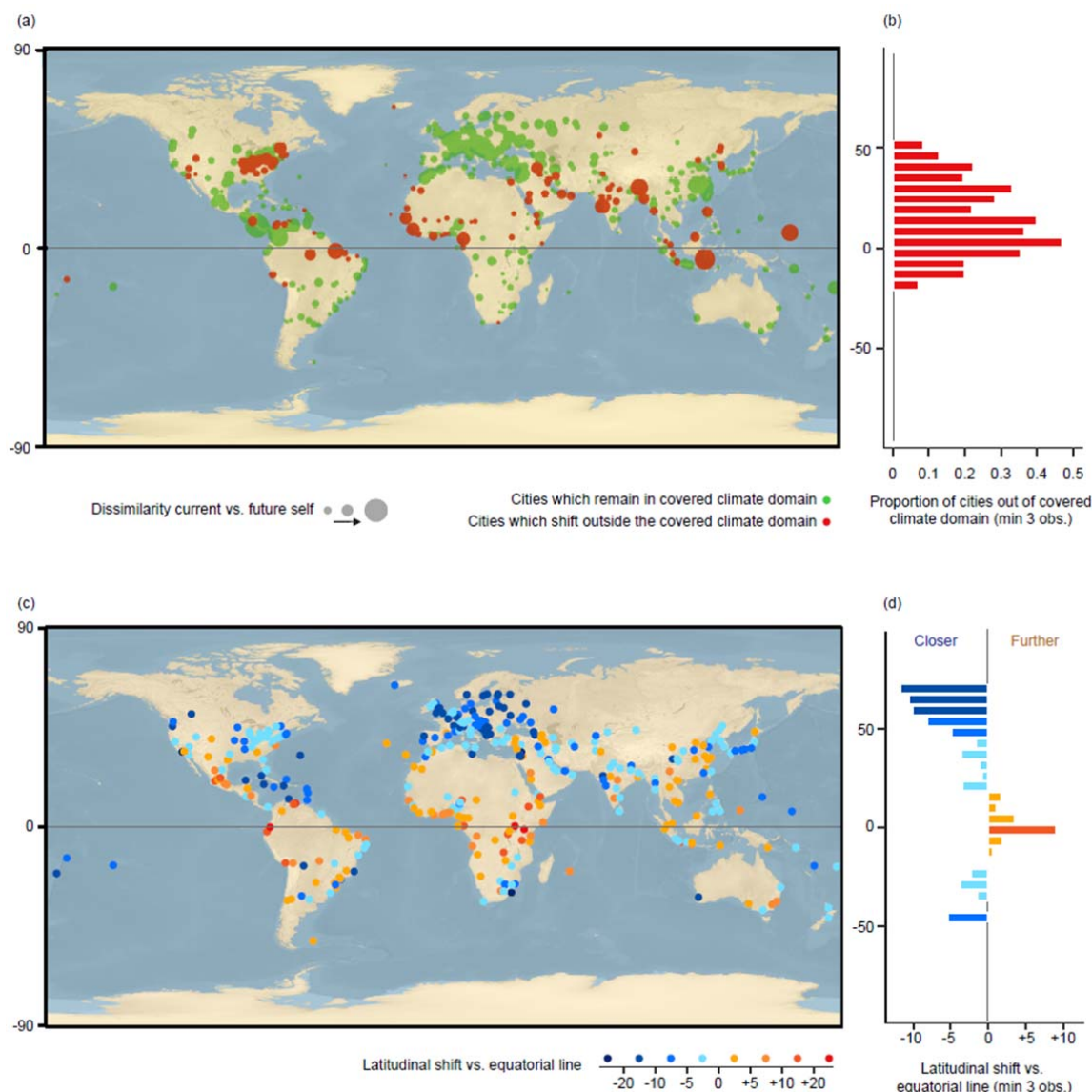
306
307 **Figure 2| Extent of climate changes in major cities of the world by 2050. a, b,** the extent
308 of change in climate conditions. Cities predicted to have climates that no major city has
309 experienced before are colored in red (mostly within the tropics). Cities for which future
310 climate conditions reflect current conditions in other major cities of the world are shown in
311 green. The size of the dots represents the magnitude of change between current and future
312 climate conditions. **b,** The proportion of cities shifting away from the covered climate domain
313 (concentrated in the tropics). **c,d,** The extent of latitudinal shifts in relation to the equatorial
314 line. Cities shifting towards the equator are colored with a blue gradient (mostly outside the
315 tropics), while cities shifting away from the equator are colored with a yellow to red gradient
316 (mostly within the tropics). **d,** A summary of the shift by latitude is illustrated in a barchart,
317 with shifts averaged by bins of 5 degrees