

Global Drought Monitoring with Drought Severity Index (DSI) using Google Earth Engine

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Research Article

Keywords: Global drought index, historical droughts, google earth engine, drought

Posted Date: April 6th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-373735/v1>

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Version of Record: A version of this preprint was published at Theoretical and Applied Climatology on August 10th, 2021. See the published version at <https://doi.org/10.1007/s00704-021-03715-9>.

1 Global Drought Monitoring with Drought Severity Index (DSI) using Google Earth 2 Engine

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8 Abstract

9 Impacts and repercussions of certain disasters could be seen immediately while other disasters like drought show their
10 deadly effects with time. Droughts are scientifically studied with help of either a simple or a composite indices
11 introduced by researchers and organizations like the Food and Agriculture Organization (FAO), World Meteorological
12 Organization (WMO), and United Nations (UN), etc. DSI or drought severity index is a composite index with
13 vegetation data and evapotranspiration data as input variables. The results are acquired after standardizing the final
14 product. In this study, droughts across the globe with respect to seven continents are identified with DSI in the years
15 2001 to 2019.

16 **Keywords:** Global drought index; historical droughts; google earth engine; drought

17 1. Introduction

18 According to a special report, Managing the Risks of Extreme Events and Disasters to Advance Climate Change
19 Adaptation (SREX) released by the IPCC for climate change and natural disasters; weather extremes and climate
20 events may not appear harmful individually, but their accumulative effect can be seen in the form of deadly droughts
21 with time (IPCC 2012). During a dry season the water demand of society and the available amount falls short (Elhag
22 and Zhang 2018). In humid areas like the Amazon forest, a mere ten percent decrease in precipitation will not cause
23 any lasting damage, but the same situation in a semi-arid area like Northeast Brazil will be a definite cause for concern
24 (Food and Agriculture Organization of the United Nations 2019). Droughts can affect regions which are not directly
25 hit by it, forexample, if a mountainous area receives less rainfall and snow than usual and it causes dryness then the
26 areas which rely on groundwater and streams that comes from those mountains will also be subjected to impacts of
27 the dry season (IDMC 2020). Drought is one of the costliest disaster humankind faces all over the world (Wang, Li,
28 and Wei 2019). It impacts socio-economic sectors like tourism, energy, water supply, agriculture, energy,
29 infrastructure, and economy of a country (Meza, Hagenlocher, et al. 2019).

30 In 2018, a global survey was conducted for indicators and their relevance to drought assessment by a joint
31 collaboration of the United Nations (UN) university and Global Drought Observatory (GDO). The research was an
32 expensive and detailed study, focusing on the agriculture and water sector, but the summary was that a vast majority
33 of researchers voted in favor of indicator-based assessment of drought (Meza, Hagenlocher, et al. 2019). These
34 indicators are numerically computed and introduced by experts working on climate change issues. There are three
35 methods used for drought monitoring through indices: with only one index, a combination of indices, and
36 hybrid/composite indicators. The single or simple index requires only one climatic/hydro-meteorological variable for

37 its computation while a combination of multiple single indices to formulate a single composite index (WMO and GWP
38 2016).

39 Drought Severity Index (DSI) is a composite index that assimilates variables of vegetation and evapotranspiration
40 (Wang, Li, and Wei 2019). DSI is categorized mainly for measuring meteorological droughts (Zargar et al. 2011), and
41 can also be used for observing agriculture drought (Elhag and Zhang 2018). It was first introduced by Mu et al. (2013)
42 using the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite NDVI and Evapotranspiration products
43 for the computation. In this study, however, instead of taking the mean of the yearly maps, the statistical median is
44 opted because it gave clearer and more accurate results. Also, the results are discussed in much more detail for almost
45 every country throughout the globe.

46 Google Earth Engine (GEE) is a cloud-based platform and runs on Python API and Java scripting (Gorelick et al.
47 2017). It is a powerful tool when dealing with big geo-datasets. It is also faster than traditional softwares and can
48 reduce the processing time in half. GEE also has a large number of datasets available in its repository that can be
49 readily used by researchers with a single line code.

50 **2. Materials and Methods**

51 **2.1 Datasets**

52 Two datasets are used in this study and all freely available in the repository of GEE; MODIS satellite terra sensor net
53 Evapotranspiration 8-Day Global 500m (Mu et al. 2007) and MODIS Terra Vegetation Indices 8-Day Global 500m
54 (Didan et al. 2015). The first one has a spatial resolution of five hundred meters, the cadence of eight days, and an
55 availability date of January 2001 to present, while the latter dataset has the same spatial resolution and cadence but
56 the availability date is from February 2000 to the present. The products used in this study from the first dataset are
57 evapotranspiration and potential evapotranspiration values while in the latter dataset the values of NDVI are used in
58 the study.

59 Evapotranspiration in a way studies the ecosystem which in extension analyzes the carbon, water, and energy cycle.
60 The ratio of ET to PET determines the available water in a terrestrial environment and helps in studying dry seasons
61 in a region (Mu et al. 2012). The agriculture sector is the one most affected by droughts at the beginning of this disaster
62 and almost eighteen percent of the global population is employed in this sector (Meza, Siebert, et al. 2019).

63 **2.2 Methodology**

64 In this study, MODIS terra data is used for analysis and computation. The parameters used in this index are
65 evapotranspiration (ET), potential evapotranspiration (PET), normalized difference vegetation index (NDVI).

66 Before computing DSI, the preprocessing performed on datasets is cloud percent reduction, shadows removal, filtering
67 timeline of our study, rescaling values to monthly data, and masking vegetation data.

68 The methodology for computation is: First, the ratio between evapotranspiration and potential evapotranspiration is
69 computed. In the second step, the ratio is standardized. Thirdly, the precomputed product of NDVI from MODIS is
70 standardized. Fourthly, the sum of both standardized values is calculated. In the final step, the sum from the previous
71 step is standardized and that value is named drought severity index or DSI.

72 The equations of the study are:

$$Tran = ET/PET \quad (1)$$

In the above equation, Tran denotes the symbol for the ratio between the input variables. ET means evapotranspiration and PET symbolize potential evapotranspiration.

$$Z1 = \frac{Tran_i - Tran_{mean}}{Tran_{SD}} \quad (2)$$

In equation 2, Z1 represents the symbol of the standardizing ratio for the transpiration ratio calculated in equation 1. $Tran_i$ means transpiration ratio of the specified eight day period, $Tran_{mean}$ symbolizes transpiration mean/average, and $Tran_{SD}$ indicates the value of the standard deviation for the transpiration ratio.

$$Z2 = \frac{NDVI_i - NDVI_{mean}}{NDVI_{SD}} \quad (3)$$

In equation 3, Z2 represents a symbol of the standardizing ratio for the NDVI values. $NDVI_i$ indicates NDVI value of the specified eight day period, $Tran_{mean}$ symbolizes NDVI mean/average, and $Tran_{SD}$ indicates the value of the standard deviation for the NDVI value of a specified period.

$$Z = Z1 + Z2 \quad (4)$$

Z represents the sum of standardized values from equations 2 and 3.

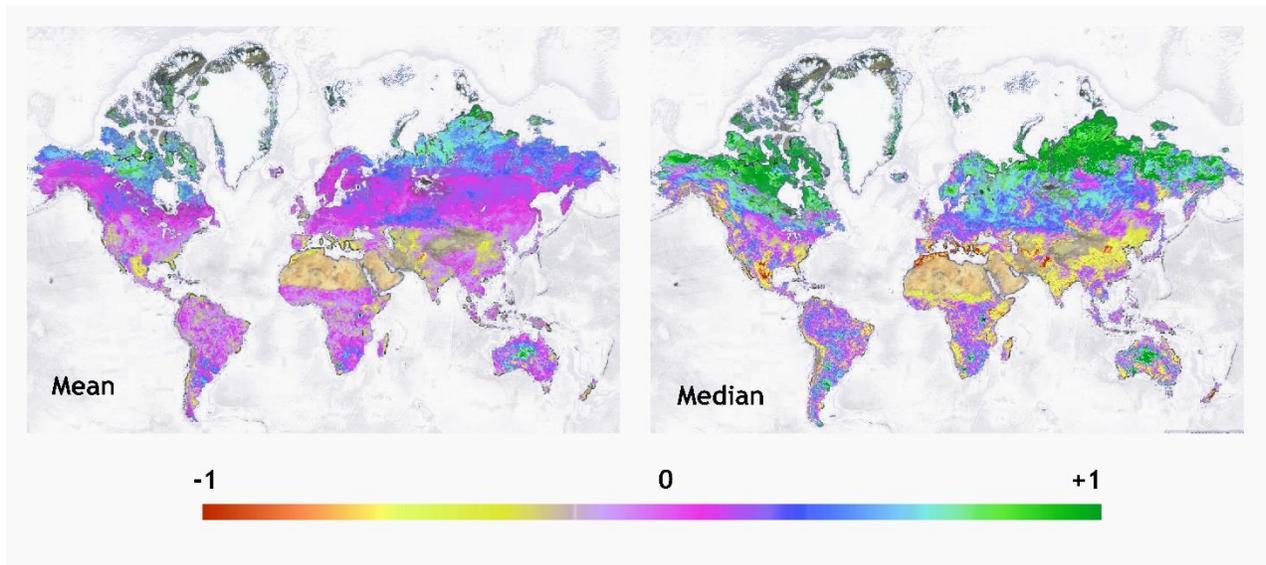
$$DSI = \frac{Z_i - Z_{mean}}{Z_{SD}} \quad (5)$$

73 In equation 5, DSI denotes the drought severity index and is standardizing the ratio for the Z values from equation
 74 4. Z_i is the value of the specified period, Z_{mean} symbolize mean/average, and Z_{SD} indicates the value of the standard
 75 deviation for the Z value of a specified period.

76

77 **3. Results**

78 For spatial maps, the statistical median is computed for the final product for the yearly result. The reason for not taking
 79 mean instead of the median is that the results are shown more clearly. A visual aid, for this reason, is shown in figure
 80 1 with 2001 as an example. The range chosen is from -1 to +1, which means extreme droughts will have values below
 81 -1 and extremely wet zones will have values above +1. The results discussed will mostly include extreme cases.



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Figure 1: Right side map shows the mean value of twelve months while the left side map is the statistical median for the year 2001.

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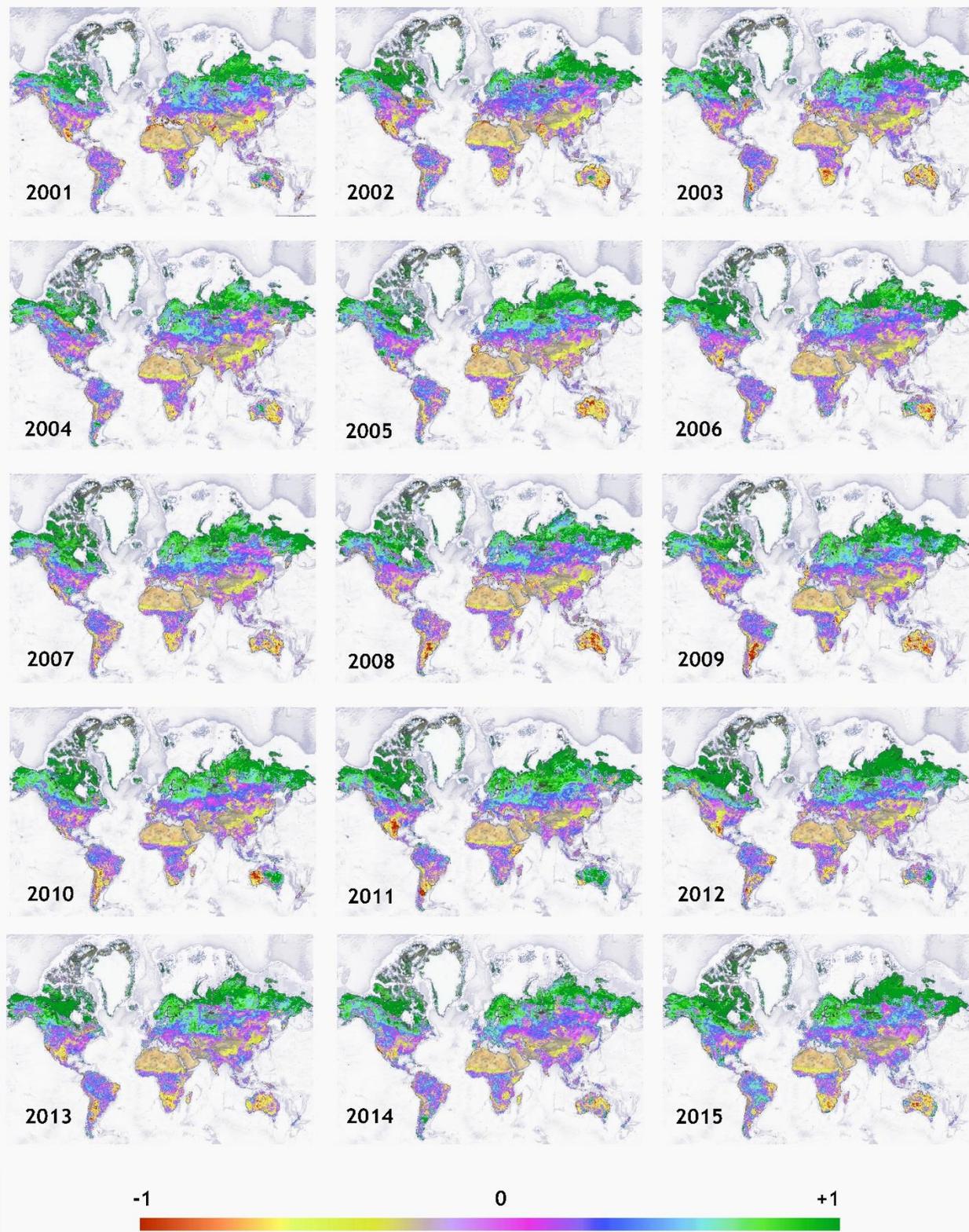
The maps are read in close detail on the GEE map by zooming in and slightly reducing the opacity to observe the

85

boundaries of countries. The maps shown in figure 2 are at a hundred percent opacity and zoomed out to cover the

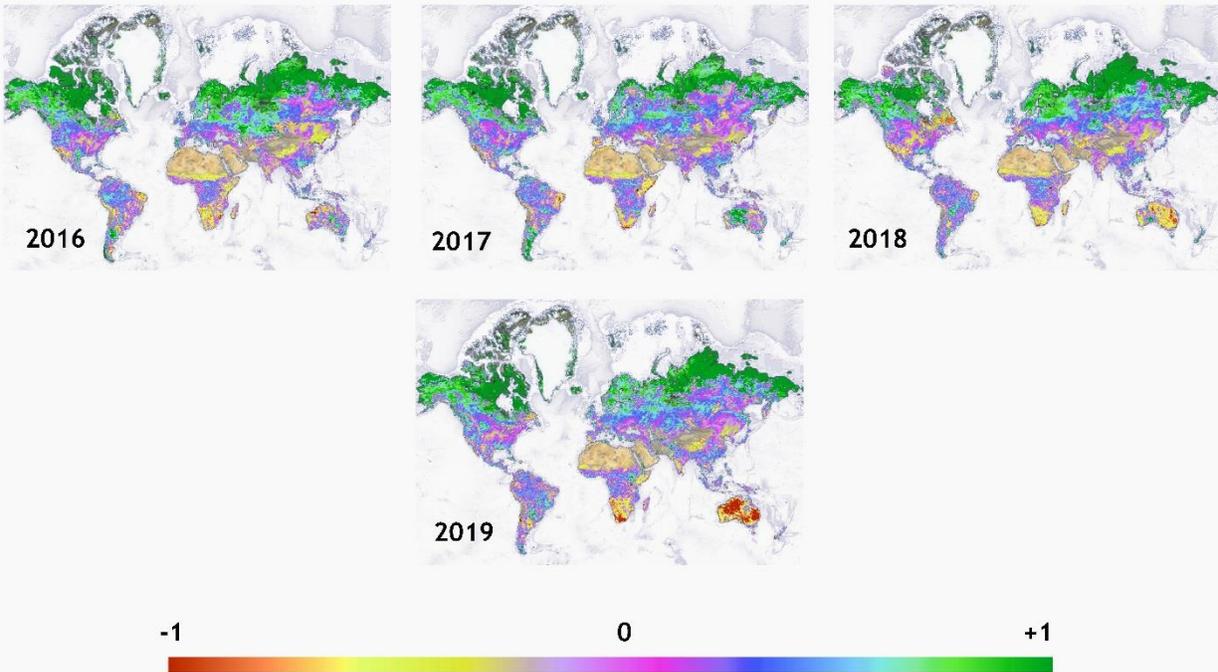
86

whole globe. The results are discussed in detail below.



87
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Figure 2a: Spatial maps of DSI from 2001 to 2015



89
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Figure 2b: Spatial maps of DSI from 2016 to 2019

91 3.1 North America

92 **2001:** More than half of Mexico is going through an extremely dry season. In the United States; Texas, Oklahoma,
93 and California show dark red patches of extreme drought; North Carolina, South Carolina, Georgia, San Francisco,
94 and Florida have mild and severe droughts in certain areas. The Dominican Republic has extreme and mild dry
95 situations in certain areas.

96 **2002:** Arizona, California, Texas near the Mexico border, and Southern Nevada in the United States are facing extreme
97 dry seasons. Kansas and Colorado are facing mild to severe drought. Mexico has an extreme drought in certain parts,
98 and severe and mild in others. Quebec and Ontario in Canada are displaying red patches of extreme and severe dry
99 situations.

100 **2003:** In the United States, Texas is facing extreme drought, California and New Mexico have mixed severe and
101 extreme dry situations. Mexico is going through an extreme and severe dry period near the United States border.

102 **2004:** Cuba is facing extreme dryness while Arizona and the neighboring areas are going through mild and severe dry
103 periods.

104 **2005:** The only notable dry patch in the whole continent is in the middle of Mexico that ranges from mild to severe.

105 **2006:** Mild to Extreme dry situation found in Mexico towards the North and in Texas and Oklahoma in the United
106 States. Mild dryness can also be seen towards California and Arizona in the United States.

107 **2007:** Arizona and California in the United States and Baja California in Mexico are showing cases of severe to
108 extreme droughts.

109 **2008:** Mild to a greater extent and severe in small areas a drought season could be noticed in the whole Mexico and
110 Texas, Arizona, California, and Nevada in the United States.

111 **2009:** Texas has severe to extreme drought. The states of Nevada, California, Arizona, and New Mexico in the US are
112 going through cases of mild to severe droughts. Mexico has also spots of severe and mild dryness near the US border.
113 **2010:** Mild to slightly severe dryness in a very small area is noticed towards the east of the United States.
114 **2011:** This year shows the worst case of the extreme dry season that spans over Texas, the majority of New Mexico
115 and Oklahoma, and some parts of Arizona and Kansas. Mexico also seems to be suffering from an extreme drought
116 that has reached almost every part of the country.
117 **2012:** In the US, the states of Texas and New Mexico are displaying evidence of mild to severe and slightly extreme
118 dry season. Mexico has a large patch of extreme drought.
119 **2013:** The state of California in the US is extremely dry this year. Colorado, Texas, and New Mexico in the US are
120 ranging in dryness from mild to extreme. The country of Mexico has also mild to the severe dry season.
121 **2014:** In the US, the states of Texas, California, and a small part of Nevada towards the south are in the throes of
122 extreme drought. Mexico has recovered slightly from the last three years' worst drought but there are still signs of
123 mild and severe dryness in parts of the country, especially the ones near the US border.
124 **2015:** California state in the US and the Gulf of California in Mexico are the only regions with cases of mild and
125 extreme dryness. The rest of the continent is exceptionally in a better state this year.
126 **2016:** The same situation is noticed this year as 2015, with the only exception of drought reducing to the south of the
127 state of California and a mild dry period in Arizona State.
128 **2017:** The states of Wyoming, Idaho, and California are the only regions in the continent this year to show small signs
129 of mild and severe dryness.
130 **2018:** The provinces of Quebec, Ontario, and Newfoundland and Labrador in Canada are extremely dry, and in the
131 United States, the regions of Texas, California, and Arizona are displaying severe and extreme dryness this year.
132 **2019:** Newfoundland and Labrador are severely dry, while in the United States, the dryness this year is in the form of
133 very small patches of extreme cases that are found in the states of Florida, Montana, California, and Wyoming.

134 **3.2 South America**

135 **2001:** Extreme dry situation is observed towards Northeast Brazil, northern parts of Venezuela, a very small portion
136 of the state of Rio de Janeiro in Brazil, towards Los Angeles and Concepcion in Chile, and San Juan and Perito Moreno
137 in Argentina.
138 **2002:** A very small region in Paraguay and Bolivia, a vast area of Santa Rosa in Argentina, and almost half of the
139 State of Mato Grosso Do Sul in Brazil are going through mild and severe dryness.
140 **2003:** Argentina is particularly dry during this year. Brazil is facing severe and mild dryness throughout the country
141 near the South Atlantic Ocean.
142 **2004:** Peru and Bolivia, a small area of Argentina, and the state of Rio Grande Do Sul in Brazil are facing mild and
143 severe dryness.
144 **2005:** Peru shows extreme cases of drought while Northeast Brazil and Argentina are mildly dry.
145 **2006:** Argentina is the only country displaying mild to extreme dryness. Mild dryness is seen towards Peru and
146 northeast Brazil.
147 **2007:** Mild and severe dry situation dominates parts of Brazil, Paraguay, and Peru. Chile is only mildly dry and in a
148 small portion. Argentina is displaying severe to extreme dryness in the middle.

149 **2008:** Argentina and Uruguay are exhibiting extreme conditions of dryness that span over a large extent of the
150 respective countries. Bolivia and Peru are displaying mild to severe droughts. Brazil in the southeast and Chile are
151 only mildly dry.

152 **2009:** A large portion of Argentina is going through extreme dryness. Paraguay, Bolivia, and the state of Rio Grande
153 Do Sul of Brazil are showing mild dry seasons. The otherwise warm and dry northeast Brazil is exceptionally wet this
154 year.

155 **2010:** Extreme droughts are noticed in a vast area of Argentina, Paraguay, and Bolivia. Uruguay, Peru, and South
156 Brazil have mild cases of dryness.

157 **2011:** Smack in the middle of Argentina is a massive dark patch of extreme drought and towards the east of the country
158 the drought ranges from mild to severe. Santa Cruz de la Sierra of Bolivia also has evidence of extreme drought.

159 **2012:** Northeast Brazil and west of Argentina both have huge evidence of extreme dry season this year.

160 **2013:** Northeast Brazil has extreme drought this year too. The drought in Argentina has not reduced in intensity but it
161 has shifted to the North where it is even spread to Paraguay and the middle of the country. Chile is also exhibiting
162 mild dryness.

163 **2014:** An almost no notable portion of northeast Brazil, north Peru, and south of Chile have severe and mild dry
164 seasons.

165 **2015:** Northeast Brazil has a severe and extreme drought. South of Chile and North of Venezuela near the Caribbean
166 Sea is also extremely dry. Argentina is mildly dry in certain parts.

167 **2016:** Northeast Brazil and South of Argentina are mild to extremely dry while Bolivia and Peru are mild to severely
168 dry.

169 **2017:** The only case of drought this year is seen towards northeast Brazil and it is mild to extreme.

170 **2018:** Drought of northeast Brazil has reduced from extreme to slightly severe and a mild case of dryness has also
171 emerged in a small area of Argentina.

172 **2019:** Chile has an extreme case of dryness and Argentina has mild and severe small dry patches in the middle of the
173 country.

174 **3.3 Africa**

175 **2001:** The only vegetative parts lie near the river banks in Tunisia and Algeria, and they are in extreme dry situations.
176 Morocco as a whole is going through a dry season. Somalia and the parts of Ethiopia that share a border with Somalia,
177 and Madagascar are in extreme and mild dry season periods in one part or the other.

178 **2002:** Severe and extreme situations are observed in Namibia, Northern parts of South Africa, a small area in Zambia
179 towards the south, and in Botswana. Western Kenya, Tunisia, Algeria, and North Eastern Uganda are facing Extreme
180 drought.

181 **2003:** Botswana and Namibia in particular are going through extreme dry periods. South Africa is facing mild and
182 extreme droughts throughout the country. A small part of Algeria and Morocco are facing severe dryness.

183 **2004:** Botswana and South Africa are having extreme dry seasons while Namibia is only mildly dry.

184 **2005:** Ranging from extreme to severe droughts are noticed in Zambia, South Africa, Tanzania, Botswana, Morocco,
185 Namibia, and Angola. Algeria, Mozambique, and Kenya show mild dry seasons.

186 **2006:** Algeria has a small severe dry patch while Kenya, Ethiopia, Madagascar, and Tanzania have mild dryness.

187 **2007:** Morocco is extremely dry while Zimbabwe, South Africa, Botswana, Namibia, and southern Angola are ranging
188 in dryness from mild to severe and extreme.

189 **2008:** Algeria and Morocco are severe to extremely dry. Somalia, Ethiopia, Zimbabwe, Mozambique, and Botswana
190 are exhibiting mild to severe dryness. South Africa and Namibia are mildly dry and only in certain parts.

191 **2009:** A small part of South Africa that lies to the south of the country and all of Kenya are displaying extreme
192 droughts. Somalia and Ethiopia are showing mild and slightly severe dryness.

193 **2010:** Somalia and two separate regions in South Africa; one to the north and other to the south are displaying clear
194 signs of extreme dryness. South of Madagascar has also some signs of severe drought.

195 **2011:** Somalia, Ethiopia, and Kenya are enduring extreme droughts this year. A very small region in Sudan is showing
196 signs of severe dryness while the rest of the country is mildly dry per usual. South Africa and Namibia are
197 exceptionally wet this year.

198 **2012:** Zimbabwe, South of Mozambique, and Botswana are exhibiting signs of dryness that range from mild to
199 extreme. There is a small straight line of severe drought passing through Ethiopia. West of Angola and Southeast of
200 Kenya are also mildly dry.

201 **2013:** Botswana, northeast Namibia, the center of Zimbabwe and South Africa, and southwest Angola are mild to
202 extremely dry.

203 **2014:** There are no severe or extreme droughts this year. The whole continent is mostly in no drought situation or
204 mildly dry.

205 **2015:** Ethiopia, Kenya, Tanzania, Zimbabwe, and Mozambique are mildly dry while the majority of South Africa,
206 south of Angola, North of Namibia, and regions of Botswana near the South African border are facing extreme dry
207 seasons.

208 **2016:** The most extreme drought noticed on the map lies to the south of Mozambique in the form of large and dark
209 patches of red. Areas near the shared border of South Africa and Botswana are experiencing mild to extreme dryness.
210 Namibia has a moderately severe case of drought that covers most of the country's north side. Tunisia, Morocco,
211 Algeria, and the rest of South Africa are mildly dry.

212 **2017:** Extreme cases of dryness are noticed; to the east of the continent in Somalia, Kenya, and Tanzania; to the north
213 in Morocco, Algeria, and Tunisia; and towards the south in the South Africa region. Madagascar and Ethiopia are
214 mildly dry.

215 **2018:** Southern regions of both Madagascar and South Africa are extremely dry. Namibia, Botswana, and Guinea are
216 mildly dry.

217 **2019:** South Africa has the worst case of extreme dryness that extends to more than half of the country. The vast area
218 of Namibia is severely and extremely dry while small regions of Mozambique and Angola are mild to severely dry.
219 Somalia, Kenya, Zambia, and Morocco are mildly dry.

220 **3.4 Europe**

221 **2001:** Extreme droughts are observed in Greece, Northeast and Southeast parts of Spain, more than half Italy, southern
222 parts in Albania, a very small part in Romania and Bulgaria that are near the black sea, and western Turkey. Madrid
223 in Spain is going through a mixture of the mild and severe dry season.

224 **2002:** The only red patch this year in Europe is found in Italy towards the south and in Zaragoza in Spain.

225 **2003:** France, Italy, and the UK are facing severe and extremely dry seasons in certain parts.

226 **2004:** No extreme or severe situation was noticed in Europe this year.
227 **2005:** Portugal and Spain are facing extreme and severe drought situations throughout the whole region. The rest of
228 the continent shows no anomalies.
229 **2006:** Spain shows mild to severe dry periods throughout the country while France has mild dryness towards the areas
230 near the bank of the Balearic Sea.
231 **2007:** Spain towards Barcelona, France in Monaco and neighboring areas, Italy in the middle, and Albania suffers
232 from mild to extreme dryness. Greece and West Turkey are going through mild to severe dryness situations.
233 **2008:** Mildly dry situation dominates this year for many European countries. These countries are Italy, Portugal,
234 Spain, Greece, Croatia, West Turkey, and France.
235 **2009:** Spain, Portugal, and France are mild to extremely dry while Italy, UK, and Ukraine are mild to moderately
236 severe dry this year.
237 **2010:** The dryness noticed this year is somewhere between mild and severe in the countries of the United Kingdom,
238 France, and Austria.
239 **2011:** Italy is slightly severe dry while the rest of the countries show no signs of harmful droughts
240 **2012:** A mild dryness is noticed towards Romania, France, Spain, and the south of Ukraine.
241 **2013:** the UK and small regions in France and Germany are mildly dry.
242 **2014:** Towards Southeast Spain, there is an extreme drought noticeable.
243 **2015:** Only mild dryness is noticed in Spain.
244 **2016:** Spain has a slightly severe to an extreme case of dryness towards its southeast.
245 **2017:** Portugal and especially Spain are severe to extremely dry while Sardinia in Italy is mild to extremely dry.
246 **2018:** A small patch of land in Portugal is extremely dry. France has mild to severe cases of dryness in the middle.
247 European Russia has evidence of mild dryness in a small area.
248 **2019:** Spain towards the southwest and Portugal towards the southeast are mild to severely dry. A small region in
249 France, Germany, and Austria is suffering from a mild case of dryness.

250 **3.5 Asia**

251 **2001:** More than half of Pakistan, almost all vegetation in Turkmenistan, vast areas of Afghanistan and Uzbekistan,
252 parts of Kazakhstan that are near the Caspian Sea, Shanxi, Ningxia, Henan, and Inner Mongolia in China are going
253 through extreme dry situations. The rest of China, almost the whole of India, Jordan, Syria, and Lebanon are displaying
254 a combination of mild and severe dry situations.
255 **2002:** Pakistan in the majority, parts of Azerbaijan, and Rajasthan of India are facing extreme drought. China is going
256 through a mild dry season.
257 **2003:** China is mildly dry. Pakistan in the middle and India towards the south is facing extreme drought.
258 **2004:** Pakistan is facing extreme drought while China, Thailand, and India are mildly dry.
259 **2005:** India and China are going through dry periods that range from mild to severe in certain parts. Thailand and
260 Vietnam show extreme to severe drought conditions while Cambodia is mildly dry.
261 **2006:** Mild drought in the majority China, Turkmenistan, and India while Severe in very small areas of the same
262 countries are the dominant droughts this year in Asia. Uzbekistan and Pakistan have mild droughts.
263 **2007:** Mild to severe droughts are found towards East Turkey, Cyprus, Turkmenistan, Uzbekistan, and India. Syria
264 and China are mildly dry.

265 **2008:** A large number of countries are showing severe and extreme droughts this year. The Republic of Cyprus, Turkey
266 towards the southeast, Turkmenistan, Afghanistan, and Iraq has dryness ranging from severe to extreme. Uzbekistan,
267 Syria, Tajikistan, Iran, Yemen, and Saudi Arabia have drought situations ranging from mild to extreme. Severe and
268 mild droughts are also seen in China and Indonesia.

269 **2009:** Iraq, Iran, and Yemen are severe to extremely dry. China, Pakistan, Turkmenistan, and India are having dry
270 seasons in the range of mild to slightly severe.

271 **2010:** Patches of extreme and severe droughts are seen in Syria, Iran, Iraq, Turkey, Lebanon, Israel, Turkmenistan,
272 the southeastern corner of Russia. Those with mild dryness are China, India, Myanmar, Thailand, Uzbekistan, and
273 Cambodia.

274 **2011:** A very small area in the southeast corner of Pakistan, vast areas of Uzbekistan, and Turkmenistan are extremely
275 dry while China, Tajikistan, Iran, and Iraq have mild dry seasons.

276 **2012:** China has evidence of severe dryness in more than one province. India and Turkmenistan have certain areas
277 that are dry in the range of somewhere between mild and severe. In Pakistan, extreme cases of dryness are seen in
278 Potohar and Sindh.

279 **2013:** Mild to severe dryness is seen towards Qinghai, Tibet, and Henan provinces of China, and also towards Syria
280 and neighboring countries, and towards the south of India. Aktau Aktay of Kazakhstan and west of Turkmenistan and
281 extremely dry.

282 **2014:** Southern corner of India, vast areas of Turkmenistan and Azerbaijan, and a small area towards the west of
283 Afghanistan are in extreme and severe drought situations.

284 **2015:** Only mild dryness is noticed this year and is found towards China, Pakistan, Iran, Iraq, and Syria.

285 **2016:** Small regions in Afghanistan, Uzbekistan, Iran, Syria, and neighboring countries, and Thailand have patches of
286 extreme dryness. The areas near the shared border of Mongolia and Russia on both sides are severely dry.
287 Turkmenistan, Pakistan, and India have evidence of mild dryness in certain areas.

288 **2017:** Syria, Iraq, and the South of India have evidence of mild to severe dryness. China is mildly dry.

289 **2018:** Afghanistan, Uzbekistan, Turkmenistan, Iran, and Pakistan show extreme patches of dryness

290 **2019:** Extreme dryness is found in China, India, Azerbaijan, and Cambodia. Turkmenistan, Pakistan, Iran, and Yemen
291 are exceptionally wet this year.

292 **3.6 Australia**

293 **2001:** Southeastern parts of New Zealand are in the claws of extreme drought. Australia has a combination of mild
294 and severe drought throughout South Australia, West Australia, and Queensland.

295 **2002:** Except for a small portion in the middle of Australia, the whole country is in the clutches of the severe and
296 extreme dry season.

297 **2003:** Severe and extreme dry situation is noticed towards the south of New Zealand and the whole of Australia.

298 **2004:** Mild and extreme dryness is noticed towards Queensland and New South Wales. South Australia and Northern
299 territory are going through a severe and mild drought.

300 **2005:** Northern Territory and Western Australia have extreme dryness, Queensland and New South Wales display
301 severe to extreme dryness, and South Australia shows mild to severe dry patches.

302 **2006:** Extreme and severe drought spans over the whole area of Queensland and New South Wales while the Northern
303 Territory and South Australia are having almost the same intensity of drought but limited to certain areas.

304 **2007:** Towards the north, the drought is mild, but going towards the south makes the drought from mild to extreme.
305 Even the otherwise cold region of Tasmania is going through a severe dry phase. New Zealand is also displaying
306 severe and mild dryness in certain areas.
307 **2008:** Queensland is displaying less severe drought as compared to the rest of Australia where extreme and severe
308 droughts are dominating the map.
309 **2009:** Mild to severe dryness is spanning over almost the whole country of Australia except for Tasmania.
310 **2010:** This year extreme drought is confined only towards Western Australia. New Zealand is mildly dry in certain
311 areas. It is also a good point to notice that the majority of Australia is extremely wet this year.
312 **2011:** Mild to slightly extreme dryness is noted only in the southwest corner of Western Australia. The rest of the
313 continent is exceptionally wet.
314 **2012:** Dryness noticed this year is relatively in a small area and is mostly mild and extreme in very small patches.
315 **2013:** New South Wales and far west of Western Australia the only areas with a mild dryness. The rest of the territories
316 of mainland Australia have severe to extreme droughts.
317 **2014:** Mild to extreme droughts are noticed all over mainland Australia with moderate patches of wet areas in between
318 too. All in all, the situation is dire but not as intense as some years.
319 **2015:** Once again droughts ranging from mild to extreme are a common sight this year in mainland Australia. Cheviot
320 and neighboring areas in New Zealand near the back of River Tasman has a bright red patch of extreme dryness.
321 **2016:** Extreme dryness patch noticed this year is relatively small and is found in the northwest part of Western
322 Australia. The rest of the mainland has mild dryness and no droughts at all.
323 **2017:** No notable dryness is noticed this year.
324 **2018:** South Australia and Western Australia have mild to the severe dry season while the rest of the territories of
325 mainland Australia are exhibiting mild to extreme dry periods.
326 **2019:** Worst case of dryness is noticed this year that ranges from severe to extreme and is covering almost the whole
327 of mainland Australia.
328

329 **5. Discussion**

330 Mexico has a warm and dry climate towards the north and annual rainfall of fewer than a hundred millimeters, whilst
331 towards the south of the country the climate is wet tropical and the annual rainfall exceeds beyond three-thousand
332 millimeters (Méndez and Magaña 2010). From our results, we have observed that droughts in Mexico are mostly
333 observed of extreme nature and are more than often occurring towards the north of the country. It is also observed that
334 droughts in Mexico and Southern states of the United States occur in most cases at the same time and of the same
335 intensity.

336 The USA has been the focus of droughts and other natural disasters for a long time (Kogan 1997), and it has been
337 observed through many research studies that perhaps greenhouse gasses and anthropogenic activities contribute a lot
338 towards the recurring droughts in states like California (Folger and Cody 2015). Research has proven that droughts
339 towards the southeast of the USA mostly occur due to the dwindling soil moisture and extreme heat (Xu et al. 2018).
340 Our study points out that in the current century the areas most affected by extreme and severe droughts in the United

341 States are the states of; Texas, California, Nevada, and Arizona. Other states such as Florida, New Mexico, and Kansas
342 also suffer from frequent droughts that range from mild to severe in intensity.

343 South America has suffered a great deal due to drought in the two decades of the twenty-first century; Northeast Brazil
344 in 2010-2016, Southeast Brazil in 2014-2015, Amazonia in 2005 and 2010, and Bolivia in 2016 (Marengo Orsini et
345 al. 2018). The results of our study point towards recurring and extremely dry seasons towards Brazil and Argentina.
346 Our studies also regard some of mild to severe droughts towards Peru, Chile, and Venezuela.

347 Argentina is the largest crop yielding country of South Asia and thus making it important agriculture wise (Kogan
348 1997). The impacts of droughts on the agriculture sector are of particular interest because it heavily depends on the
349 water which is a basic need for survival for all living beings, and also a hit to agriculture has caused massive famines
350 in the past (Meza, Siebert, et al. 2019). Northeast Brazil has ninety-five percent farmland dependent on rain and adds
351 to the fact that a high percentage of its inhabitants live in poverty, so naturally, the impacts of droughts on this region
352 are severe (Cunha et al. 2018). The increased dry seasons in Brazil have made policymakers, scientists, and
353 government worried over its impacts on the socioeconomic, food, and the fast-shifting of some of the lands towards
354 desertification (Marengo, Torres, and Alves 2017).

355 The results of our study indicate that in the continent Africa the worst cases of droughts are noticed towards Eastern
356 Africa, Southern Africa, and the Northern parts. In the center of Africa, the situation is not that dire and there are
357 almost no signs of extreme to severe dry seasons. The region of Madagascar also suffers from time to time due to
358 severe dryness and mostly towards the south of the Island. In Eastern Africa, the countries suffering more frequently
359 and the most are Ethiopia and Somalia. Kenya also goes through extreme dry seasons but not as much as the other
360 two countries. South Africa suffers from extreme droughts but other countries of South like Namibia, Botswana,
361 Zimbabwe, Mozambique, and Angola also go through severe and extreme dryness frequently. Towards the north;
362 Morocco, Algeria, and Tunisia went through extreme droughts at the beginning of the century and then through severe
363 and mild dry seasons for the rest of the vast majority of the century.

364 African countries are prone to droughts and have already pushed many countries towards desertification and its impact
365 on agriculture has raised food insecurity in the inhabitants (Eckstein et al. 2020). Meza et al., (2019) concluded in
366 their research that the ten countries most vulnerable to droughts are: Zimbabwe, Namibia, Botswana, Morocco,
367 Kosovo, East Timor, Mauritania, Lesotho, Kazakhstan, and Algeria. Seven out of ten of the aforementioned countries
368 belong to the African continent. According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel
369 on Climate Change (IPCC), there is a high probability of reduced annual rainfall towards Northern Sahara Africa and
370 Mediterranean Africa. There is also a high chance of reduced rainfall in the winter season towards South Africa and a
371 slight increase in annual mean of precipitation towards Eastern Africa (Knox et al. 2012). Studies indicate that
372 anthropogenic activities in the Indian Ocean caused the warming of the ocean which reduced the precipitation rate by
373 fifteen percent in the crop growing seasons towards the eastern and southern Africa, and as a result, the crop yield is
374 severely impacted all across sub-Saharan Africa (Conway and Schipper 2011).

375 Ethiopia has faced some intense mega droughts and suffered the consequences. The drought in Ethiopia in 2009 alone
376 affected six million people and the country had to rely on foreign aid to deal with the aftermaths (Bayissa et al. 2018).
377 Similarly, in 2015-2016, an El Nino event triggered an extreme drought towards eastern Africa that affected ten million
378 inhabitants of Ethiopia, and once again the issue of food insecurity was risen (Delbiso et al. 2017). Evidence is

379 available that suggests the cause of the 2015 drought in South Africa was due to sea surface temperature change which
380 leads to high atmospheric temperature and less rainfall (Eckstein et al. 2020).

381 For Europe, the results in this study conclude that extreme and severe dry seasons are not that common when compared
382 to the rest of the continents. The countries that show signs of extreme dryness for more than once in the recent century
383 were: Spain, Portugal, France, and Italy. Other countries were either very small to notice on the map or were suffering
384 from mild dry seasons and not condemning its inhabitants to food insecurity. The other notable point in the study was
385 the coincidence of droughts occurring more than once at the same time in Portugal and Spain. France also joined
386 sometimes in the dryness when these two countries were suffering but not that often. Italy showed signs of extreme
387 dryness that were noteworthy on more than one occasion and that spread to a larger portion of the country.

388 Climate Model studies have predicted that there would be a significant decline in the precipitation level in the
389 Mediterranean region and the countries will get affected in the agriculture sector due to the dryness (Vicente-Serrano
390 2007). Droughts towards this region however have shown no lasting impact on the gross primary production of the
391 vegetation (Vicca et al. 2016). Extreme events in this continent have impacted biodiversity in the form of endangering
392 of species, heat waves, migration of animals, and a rise in the carbon dioxide level (Thuiller et al. 2005).

393 The results of our study in the case of Asia are suggesting the vulnerability of certain countries to frequent and extreme
394 droughts, namely: Pakistan, Kazakhstan, India, China, and Azerbaijan. Other countries like Afghanistan, Syria,
395 Turkmenistan, Iran, and Iraq also show cases of extreme droughts at one point or another on more than one occasion.

396 The dry season in India, Turkmenistan, and China are though extreme but they seldom cover the vast majority of the
397 country. Pakistan, Azerbaijan, and Kazakhstan, on the other hand, show cases where more than half of the country's
398 agriculture is under the thrall of extreme dry season. Countries in the neighboring of Syria like Israel, Lebanon, and
399 Jordan, etc. also showed signs of severe droughts at one point or another.

400 Agriculture and livestock are the main sources of income for more than half the population of people living in rural
401 areas of South Asia and the recent climate change is hitting that sector hard (Knox et al. 2012). Similarly, in South-
402 East Asia, another agriculture-dependent region, droughts are a frequent occurrence and mostly hit during the seasons
403 when the El Nino phenomenon is active (ESCAP 2019). The region of Kazakhstan has only one-tenth of its land used
404 for crop sowing while the remaining is rangeland used for livestock grazing and the repeated dry seasons do not bode
405 well for either sector (Kogan 1997). Droughts in India also impact agriculture and often hit the arid and semi-arid
406 parts of the country (Muthumanickam et al. 2011). North-China is an important region for the wheat sown in winter
407 for China and droughts regularly occur in this part which is a cause of concern for both the government and the public
408 (Zhang, Mu, and Huang 2016). Pakistan is prone to droughts and despite being blessed with the heavy monsoon in
409 summer and western disturbances in the winter, almost every province of the country has suffered through a dry season
410 at one point or another (PMD 2018).

411 In this study, it was noticed that mainland Australia goes through extreme dry seasons that span over almost the whole
412 area more frequently. The only years where there were no signs of severe droughts for the study period were: 2001,
413 2011, 2012, and 2017. In 2016, there was only a small area that was affected by extreme dryness while the rest of
414 mainland Australia was going through good season precipitation wise. The other notable point in the study was;
415 Tasmania was the only region of Australia that seldom saw a dry season that span over a vast area of the Island. New
416 Zealand was sometimes observed going through mild and severe dryness but the affected area was mostly limited to
417 one or other corners of the country.

418 Climate Model studies have predicted there will be a forty percent rise in the dry seasons towards Eastern Australia
419 and the overall pattern of Precipitation will also change and so will the temperature rise (Quiggin 2010). Studies have
420 shown that in the last hundred years almost every extreme drought has occurred due to the El Nino phenomenon and
421 will continue so in the future (Braganza et al. 2003). A study published in 2005 pointed out that due to frequent
422 droughts; in the last fifty years the agriculture of the country has reduced contribution from twenty percent to only
423 five percent towards the GDP and the employment rate has also decreased (Horridge, Madden, and Wittwer 2005).
424 The droughts destroy fruits and vegetable yield in the country which leads to a shortage of supply for the general
425 public and once the demand rises the prices of almost every product spike considerably (Quiggin 2010). According to
426 the Australian crop report, ABARES, the yield of crops will fall in major areas where the agriculture sector usually
427 flourishes (ABARES 2019).

428 **6. Conclusion**

429 DSI or Drought Severity Index by using MODIS products for computation and study of drought is discussed in this
430 research and the tool employed for analysis and computation is Google Earth Engine; a cloud-based GIS and geospatial
431 tool. Droughts are seen with recurring frequency throughout the globe with certain parts experiencing more extreme
432 dry seasons than others. Continent wise, Australia, Africa, and Asia have the most extreme and frequent drought
433 events while South America and North America comes a close second. Europe is the least affected by this particular
434 weather event when compared to other continents. This study declares countries vulnerable to extreme droughts:
435 Central America and Southern Mexico in North America; Argentina, Northeast Brazil, and Southeast Brazil in South
436 America; Italy, Spain, and Portugal in Europe; Ethiopia, Kenya, Morocco, Tasmania, Zimbabwe, Mozambique,
437 Namibia, and South Africa in the African Continent; Pakistan, India, China, Azerbaijan, Iraq, Syria, Iran, and
438 Kazakhstan in Asia; and the whole mainland Australia.

439 **7. Ethical Approval**

440 Not applicable

441 **8. Consent to Participate**

442 Not applicable

443 **9. Consent to Publish**

444 Not applicable

445 **10. Authors Contributions**

446 Supervision, project administration, writing-review and editing, and validation were performed by Dr. Hammad
447 Gilani. Data curation, formal analysis, investigation, methodology, software, visualization, and writing-original draft
448 were the duty of Ramla Khan. The main idea of the research was the combined effort of both authors.

449 **11. Funding**

450 Not Funded

451 **12. Availability of data and materials**

452 All the datasets are available in the repository of Google Earth Engine. The details and specifications of each dataset
453 has already been mentioned in the subsection Datasets of Materials and Methods.

454 The links to each along with their titles are mentioned below

455 MOD16A2.006: Terra Net Evapotranspiration 8-Day Global 500m: <https://lpdaac.usgs.gov/products/mod16a2v006/>

456 MODIS Terra Vegetation Indices 16-Day Global 500m: <https://lpdaac.usgs.gov/products/mod13a1v006/>

457 KBDI: Keetch-Byram Drought Index: <https://developers.google.com/earth->

458 [engine/datasets/catalog/UTOKYO_WTLAB_KBDI_v1](https://developers.google.com/earth-engine/datasets/catalog/UTOKYO_WTLAB_KBDI_v1)

459 TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces, University of Idaho:

460 https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE

461 **13. Competing Interests**

462 The authors declare that they have no competing interests

463 **14. References**

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565

Figures

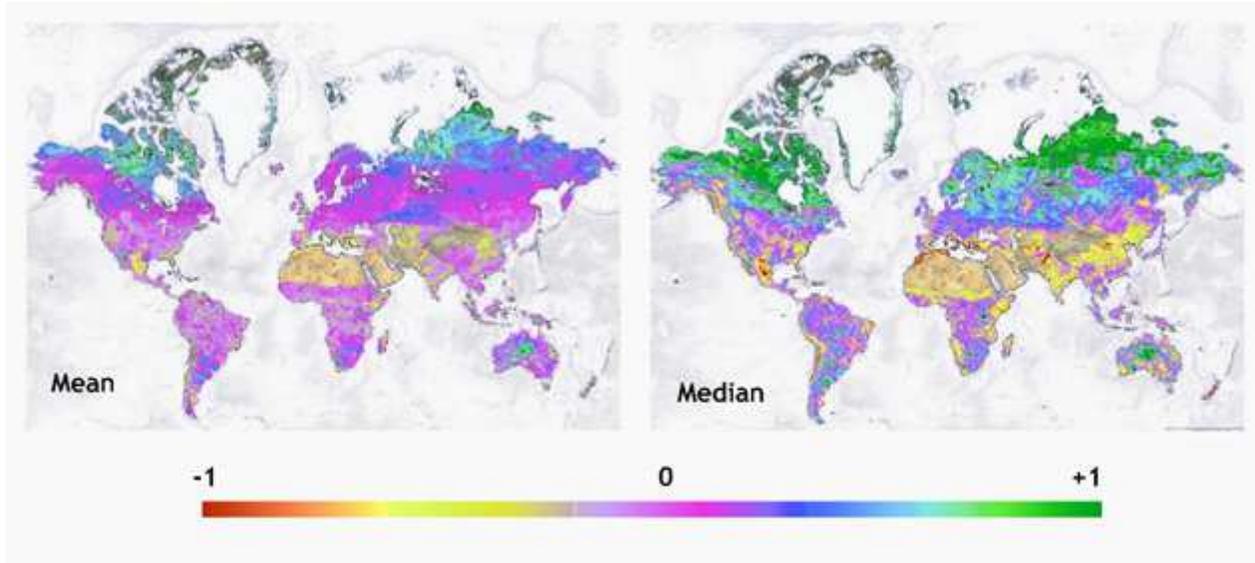


Figure 1

Right side map shows the mean value of twelve months while the left side map is the statistical median for the year 2001. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

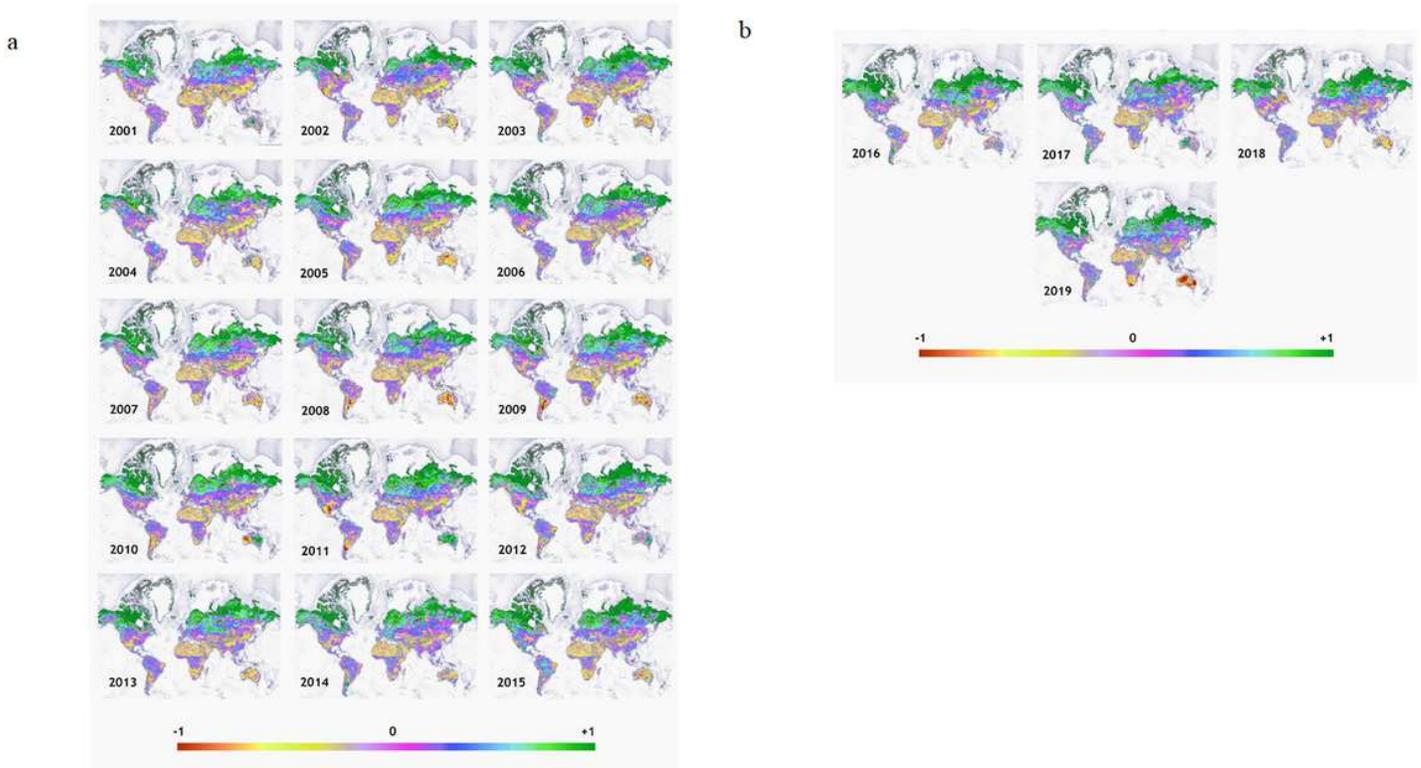


Figure 2

2a: Spatial maps of DSI from 2001 to 2015 2b: Spatial maps of DSI from 2016 to 2019 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.