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The uneven impact of climate change on drought with elevation in the Canary Islands

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Climate models project an increase in drought and aridity in many regions in response to greenhouse gas concentrations in the atmosphere. In areas with complex topography, such as the Canary Islands, elevation gradients may play an important role in future changes. Convection-permitting climate simulations driven by data from three global climate models included in the Coupled Model Intercomparison Project (CMIP5) have been performed for the Canary Islands. A significant increase in the duration and severity of drought is projected by the end of the twenty-first century (2070–2099), relative to the recent past (1980–2009), under intermediate and high emissions scenarios. In addition, the percentage of land affected by droughts, on average, would increase considerably, covering up to 96% in the higher elevations, in the business-as-usual scenario. These changes and the increase in aridity are more pronounced at higher altitudes due to a clear dependence of temperature rise as a function of elevation and a substantial decrease in precipitation.

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INTRODUCTION

Droughts, characterized by periods when moisture conditions are substantially below the long-term average for a given area¹, are one of the most significant climatic impact drivers, directly affecting society and ecosystems². Therefore, the study of their possible future variations due to climate change is of great importance. Droughts generally begin with a deficiency of precipitation, subsequently affecting the different elements of the water cycle. They are also influenced by other factors, such as vegetation, land and water management, or temperature³. Droughts are usually classified according to their temporal extent and their impact on different ecological or social environments^{1,4}. Thus, they are commonly classified into meteorological, agricultural, hydrological, and socio-economic droughts. They are mainly associated with a reduction in precipitation, a deficit in soil moisture and the consequent impact on crops, a shortage of surface or groundwater supply, and a failure of water resource systems to meet water demands, respectively.

Due to the difficulty in quantifying the different types of drought and the variables involved, which are often not available over large regions and long enough periods to carry out climate studies, some indices based solely on atmospheric variables have been defined. They can be calculated from meteorological observations or simulated data, such as reanalyses or climate model outputs. The Standardized Precipitation Index (SPI)^{5,6} has been extensively used worldwide due to the simplicity of its calculation. The index relies only on precipitation as an input variable, is applicable in all climate regimes and can be interpreted with ease⁷. It uses time series from a particular location to compute the probability of precipitation at different time scales⁵. The SPI values for 3 months or less might be useful for meteorological drought monitoring, values for 6 months or less for monitoring agricultural impacts, and values for 12 months or longer for hydrological impacts^{1,8}. As the probability distribution computed from the time series is transformed into a normal

distribution, the mean value of SPI for a particular location and period is zero. Generally, rainfall deficits are considered when SPI decreases below -1.0 , and excess rainfall when SPI increases above 1.0 ⁵. However, SPI does not consider the effect of other atmospheric variables, such as temperature, which is an important factor in water balance and water use. Therefore, it is not adequate to compare periods of similar precipitation but with different conditions for the other variables⁹. The Standardized Precipitation-Evapotranspiration Index (SPEI)⁹ was developed to overcome this limitation while preserving the aforementioned advantages of SPI. According to these indices, the beginning of a drought event is usually defined when the index falls below one negative standard deviation and ends when it becomes positive again. This makes it possible to define the frequency of such events in a given period or their severity based on the cumulative or average values of the corresponding index.

Unlike droughts, aridity measures the long-term average water supply, precipitation, compared to average water demand, and evapotranspiration. The aridity index¹⁰ indicates these long-term climatic water deficits and is defined as the ratio between average precipitation in a period and potential evapotranspiration (PET). Its simplicity allows, as in the case of the drought indices, that it can also be calculated from observational data or climate simulations. To compare a possible change in the aridity conditions of territory in two different periods, the Aridity Change Index (ACI)¹¹ can be used. It is defined as a ratio between the aridity index calculated for one each of the periods.

A previous study¹², based on observations, estimated a global increase in the extent of arid areas, those with an aridity index below 0.5 , of 1.4% for the period 1981–2010 compared to the period 1951–1980. This relative increase was more relevant in Europe ($+5.0\%$) and Africa ($+3.3\%$) than in other continents. North-Eastern Brazil, Southern Argentina, the Sahel, Zambia and Zimbabwe, the Mediterranean area, North-Eastern China, and Sub-Himalayan India were identified as areas with a significant increase

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of drylands extent. Also using the SPI and SPEI indices from observational datasets, a robust increase in drought frequency and severity between the periods 1951–1980 and 1981–2016 was found in most of those regions¹³: Patagonia, the Sahel, the Congo River basin, the Mediterranean region, and North-Eastern China.

In addition, many studies have estimated future changes in drought indices², both globally and regionally. One comprehensive study¹⁴ analyzed the possible changes in the SPI and SPEI indices at the end of the century relative to the recent past. It is based on 103 regional simulations, which were produced in the framework of the COordinated Regional Downscaling EXperiments (CORDEX) and driven by the results of 16 global climate models (GCMs) of the Coupled Model Intercomparison Project phase 5 (CMIP5). It was also based on the results from these GCMs directly. Two future climate scenarios were considered, the moderate Representative Concentration Pathway (RCP), RCP4.5, and the business-as-usual scenario, RCP8.5¹⁵. By the end of the twenty-first century, an increase in frequency and severity was found, mainly in the Amazon, southern South America, the Mediterranean region, southern Africa, and southern Australia. The increase in the frequency and severity of drought events in these regions was more pronounced using the SPEI index than the SPI, since it also considers the effect of increased evapotranspiration due to global warming. In the most unfavorable scenario, their simulations show a reduction in the frequency of drought events in some of these regions, compared to the RCP4.5 scenario, due to a much longer duration of drought events. In contrast, projections estimate a decrease in the frequency and severity of droughts over the high latitudes of the Northern Hemisphere and Southeast Asia. In some regions, the sign of the estimated change depends on the index chosen, that is, whether or not temperature is taken into account. According to the aridity index and using GCMs, major expansions of drylands are projected at the end of the century for the RCP8.5 over North America, the northern fringe of Africa, the Mediterranean, Southern Africa, coastal areas of Australia, the Middle East, Central Asia, and South America¹⁰.

For small islands, vulnerability to climate change is greater than in other regions and their resilience is more challenging¹⁶. Based on studies using global models and different climate regionalizations, it is very likely that small island regions will continue to warm in the current century, although slightly less than the global average¹⁷. Small islands in the regions of the western and equatorial Pacific, north Indian, and southern oceans are likely to be wetter in the future. However, those located in the Caribbean, parts of the Atlantic and west Indian oceans, and the southern subtropical and the eastern Pacific Ocean will be drier¹⁸. An analysis of the future change of the aridity index on 80 islands or island groups, computed from GCM results under the RCP8.5 forcing, revealed a robust, though the spatially variable, trend toward increasing aridity in more than 73% of them by mid-century¹¹. The increase in aridity is even stronger in the projections for the end of the century. The islands with the greatest increase in aridity are some located in the South Pacific, near the coast of Chile, in French Polynesia, in the Caribbean, and in the Atlantic, specifically, Madeira and the Canary Islands¹¹.

This study is focused on the Canary Islands, located in the North Atlantic, west of the coast of Africa. The territory is mountainous, especially in the western islands, reaching elevations up to 3700 m on the largest island, Tenerife. This characteristic topography makes it necessary to study the effect of climate change at different altitude levels. In fact, the positive observed temperature trend during the last decades is more pronounced at higher altitudes¹⁹. Future projections based on climatic downscaling also predict a greater temperature increase at higher elevations^{20,21}. This is in agreement with the so-called elevation-dependent warming, which is typical of tropical and subtropical regions²². On the other hand, although with some variability amongst the different sites, a general decrease in precipitation has been

estimated for the second half of the twentieth century²³, which is also projected to the end of the century, affecting once more the higher elevations of the islands with more severity²⁴. Due to this dependence on elevation, four altitude intervals have been considered for analysis, based on the thermotypes obtained in a previous study for the island of Tenerife²⁵: 0–400, 400–1100, 1100–2100, and >2100 m.

To account for the different levels of elevation on such small islands and the dependence of the climatic variables on the topography, the Weather Research and Forecasting (WRF) regional climate model (RCM) was used to downscale model data to a spatial resolution of 3 × 3 km. Model outputs of three CIMP5 models were used as initial and boundary conditions: GFDL-ESM2M (hereinafter GFDL), IPSL-CM5A-MR (IPSL), and MIROC (ESM). The simulations throughout the twenty-first century were performed assuming two concentration pathways, RCP4.5 and RCP8.5. From the results, the SPI, SPEI, and ACI indices were calculated using a period corresponding to the recent past, 1980–2009, and one at the end of the century, 2070–2099.

This work has contributed to filling the gap in high-resolution climate projections of drought in small islands and enabled the study of drought indices in the Canary Islands, where there are no previous works to the authors' knowledge. Furthermore, the study has analyzed the uneven impact of altitude in drought, up to levels above 2100 m, which could be useful in other regions of high altitudes.

RESULTS

Skills to reproduce recent past variables

Before calculating the drought and aridity indices in the study region, the ability of the regional climate simulations to reproduce the variables on which they are based (e.g., precipitation and PET) must be evaluated. In Fig. 1, data obtained from three World Meteorological Organization (WMO) stations located at three different elevations are compared with the results of the nearest gridpoint of the simulations for the recent past period. The three locations correspond to the island of Tenerife, which is the highest, allowing us to observe the different behaviors with elevation. Despite the differences between the actual station height and those extracted from the relatively coarse elevation model used by WRF, the annual cycle of the monthly mean precipitations is well reproduced by the simulations driven by the three GCMs. The largest differences are observed for the SCT station, that closest to the coast. Given the resolution of the model (3 × 3 km), the corresponding model gridpoint could be partly on land and partly on the ocean, smoothing the temperature and increasing the humidity. This leads to an underestimation of evapotranspiration during the summer months at this location. In addition, the peak in rainfall observations at the Santa Cruz station in March is due to a torrential rainfall (232.6 mm in 24 h) that affected a minute area around the capital of Tenerife in 2002.

Future changes at altitude intervals

The large spatial variability of the climate of the Canary Islands, in which topography plays a crucial role, creates a large difference in conditions in the lower islands in comparison with the higher ones, and even between windward and leeward areas of the same island. However, given the clear dependence on the elevation of the estimated future changes obtained in previous works and to simplify the analysis of the results, the four altitude intervals defined above have been used: 0–400, 400–1100, 1100–2100, and >2100 m.

Since drought periods usually start with a precipitation deficit, the expected future changes in 12-month accumulated precipitation, which is associated with hydrological drought events, were qualitatively analyzed. The monthly time series of accumulated

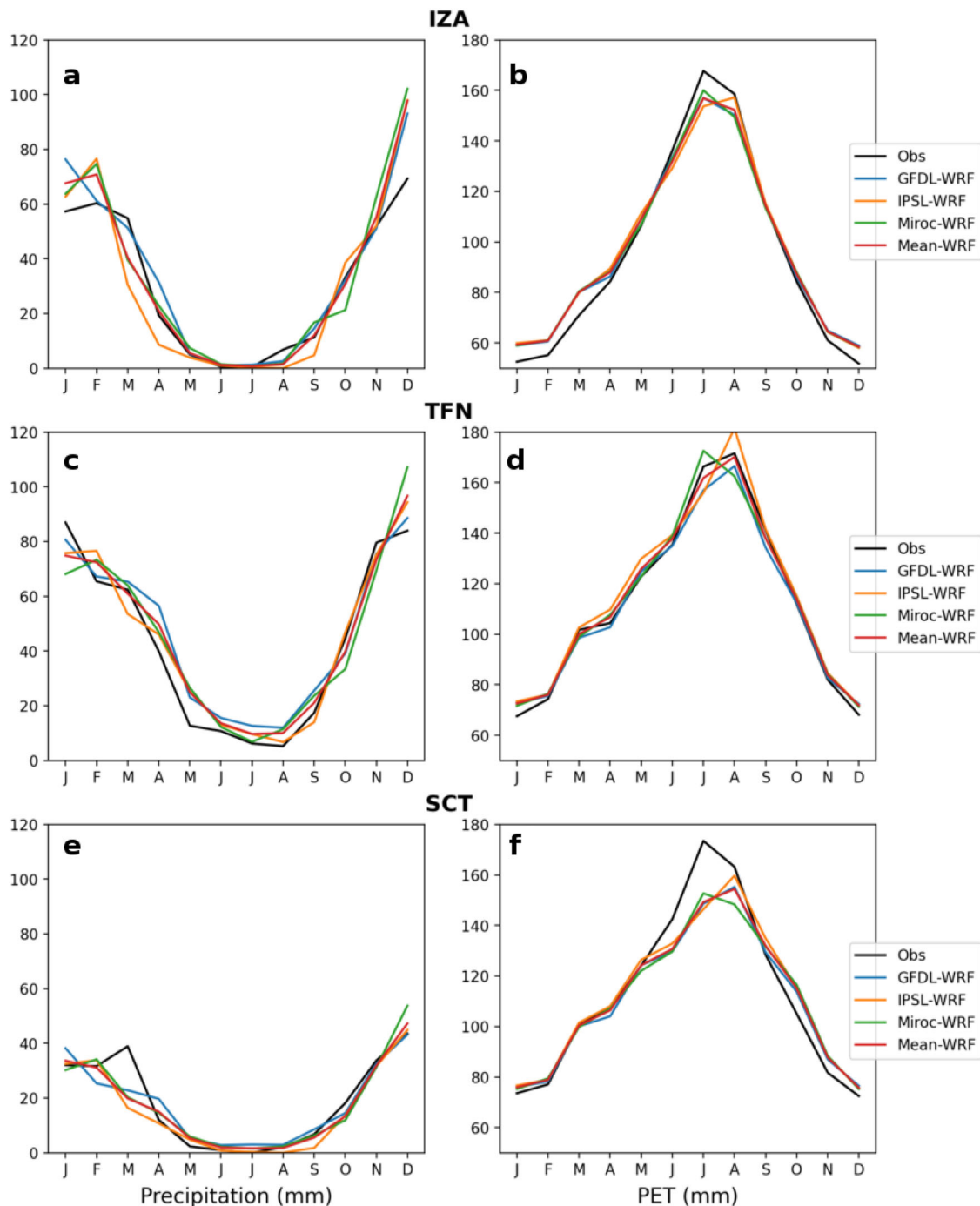


Fig. 1 Skills of WRF simulations to reproduce recent past precipitation and evapotranspiration. Comparison of precipitation (**a, c, e**) and potential evapotranspiration (**b, d, f**) obtained from observations (black line) and from WRF model results, in the recent past period, 1980–2009, in three WMO stations: **a, b** Izaña (IZA, 2371 masl), **c, d** Tenerife Norte (TFN, 632 masl), and **e, f** Santa Cruz de Tenerife (SCT, 46 masl).

precipitation, averaged for each of the four elevation levels, were fitted to a cumulative distribution function based on the log-logistic distribution (see Methods section for further details). Cumulative distributions were obtained for the 30-year period corresponding to the recent past and for the last three decades of the century using both the RCP4.5 and 8.5 emissions scenarios. Figure 2 shows the curves for the MIROC-WRF simulations, the results being very similar to those obtained with the other simulations driven by the other two GCMs models.

The higher altitude levels show larger cumulative rainfall in the recent past period (solid curves), following previous studies^{20,26}. Furthermore, projections foresee a drastic decrease in precipitation at these elevations. For interpretation purposes, the ordinates corresponding to the 50th, 15.9th, and 2.3th percentiles have been highlighted in Fig. 2. The latter two are related to moderate and extreme drought conditions, respectively. The red line indicates the value of precipitation corresponding to extremely dry in the recent past period. At lower levels, below 400 m, current

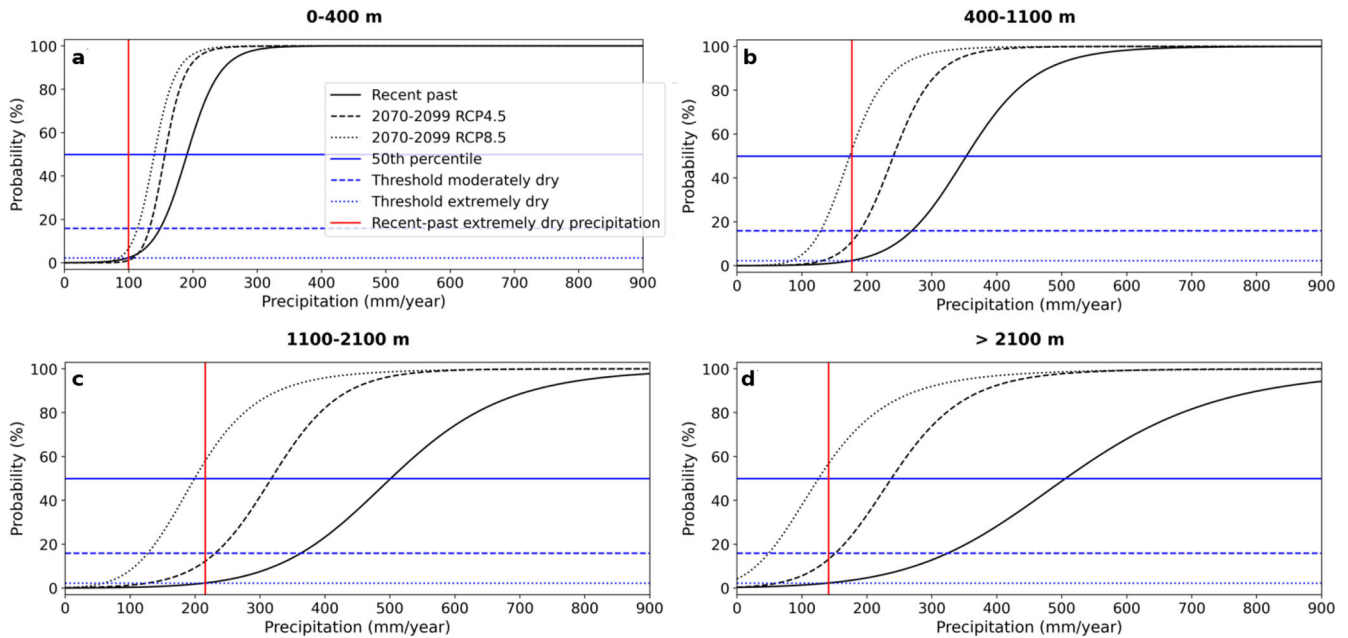


Fig. 2 Cumulative distribution functions for precipitation in the recent past and for future projections at different elevation levels. Twelve-month accumulated precipitation, in the MIROC-WRF model, at the four altitude intervals analyzed: **a** 0–400 m, **b** 400–1100 m, **c** 1100–2100 m, **d** >2100 m. The black solid curve represents the log-logistic Cumulative Distribution Functions (CDFs) for the reference period (1980–2009). The dashed lines represent CDFs fitted to the precipitation data for the future period (2070–2099) for both emissions scenarios (RCP4.5 and RCP8.5). The blue lines are the values corresponding to the 50th percentile, moderately dry (SPI = −1, 15.9th percentile) and extremely dry (SPI = −2, 2.3th percentile). The red line indicates the precipitation value corresponding to “extremely dry” of recent past.

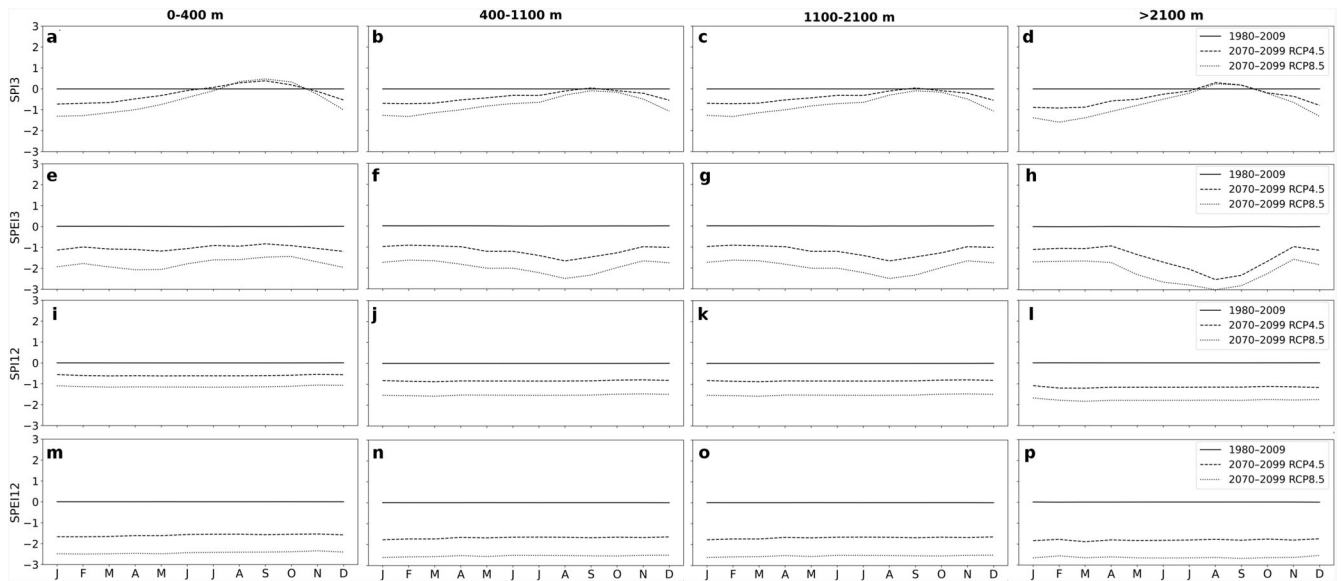


Fig. 3 Annual SPI and SPEI cycle for recent past and future projections by altitude levels. Annual cycle of SPI and SPEI at 3- (**a–h**) and 12-month (**i–p**) time scales for 30-year period simulations: recent past (1980–2009) and future 2070–2099, scenarios RCP4.5 and 8.5, at the four altitude intervals analyzed: 0–400 m (**a, e, i, m**), 400–1100 m (**b, f, j, n**), 1100–2100 m (**c, g, k, o**), and >2100 m (**d, h, l, p**). The ensemble means are presented.

precipitation is scarce and, therefore, its absolute future variation is also expected to be lower. At the upper levels, the 12-month accumulated precipitation, which for the recent past is considered to be associated with extreme drought, becomes usual at the end of the century for the worst considered scenario and would be classified as moderate drought in the RCP4.5 scenario.

In practice, the water demand in a region is dominated by seasonal characteristics¹. Figure 3 shows the monthly averages, for

the recent past and at the end of the century for the two emission scenarios, of the SPI and SPEI indices, at 3- and 12-month time scales, at the four altitude levels analyzed. Once the monthly mean for each of the simulations has been computed, the average of the resulting values has been calculated for the three simulations, driven by the different GCMs, corresponding to the same period. The recent past has been taken as the reference period to calibrate the probability distributions. Accordingly, the

mean values of all the indices for that period are null. This figure allows us to analyze the annual pattern of future droughts by altitude and to compare the two indices to deduce the relevance of evapotranspiration.

In general, drought is projected to worsen with altitude, as indicated by the larger SPI and SPEI negative values. In altitudes above 2100 m, the 3-month cumulative SPEI index reaches, in August, values of -3 , and 12-month cumulative indices are also close to -3 . Note that the minimum value of the SPI and SPEI indices had been set to -3 , which corresponds to the 0.1th percentile of the recent past period. As expected, the impact on drought indices is larger for the worst emissions scenario.

A 3-month accumulated analysis of the two indices shows a clear seasonal behavior, although different for both indices. While SPI3 increases at the end of the summer period, even reaching positive values in September, the SPEI3 index has minimum values close to -3 for those months. The explanation is in the precipitation and evapotranspiration annual cycle, Fig. 4. A very slight increase in future summer precipitation is estimated, mainly at coastal levels, which translates into SPI3 reaching slightly positive values, between August and October, at the end of the century, in both emission scenarios. However, if the SPEI3 index is analyzed, as summer precipitation is practically 0, both in recent past and future, the evapotranspiration, which reaches maximum values in this season, contributes to the overall drying. This causes low SPEI3 values in early autumn. The need to include evapotranspiration for the study of drought in semi-arid regions has been addressed in previous studies^{27–29}. Similarly, in the Canary Islands, working with indices, such as the SPI, that only take precipitation into account, can lead to different conclusions. For this reason, henceforth, the analysis will be mainly based on the SPEI, although those results corresponding to the SPI are provided in Supplementary Figs. 2 and 3 to allow comparison.

In terms of altitude, as previously commented, precipitation projections show a clear decrease. The evapotranspiration at low

levels is significantly lower than above 400 m. This is due to two factors (see Supplementary Fig. 1). Firstly, low levels correspond mainly to coastal areas, where humidity increases and the temperature remains mild. Secondly, the almost permanent cloud of stratocumulus located in the windward of the Canary Islands, due to the persistence of the thermal inversion³⁰, favors the reduction of incoming solar radiation. Evapotranspiration projections show a future increase, higher in the RCP8.5 scenario and increasing at higher levels, mainly due to a larger increase in temperature at higher elevations and a higher decrease in humidity. These results are in agreement with global studies³¹. They stated that precipitation was the dominant driver for the changes in the water budget before the early 1980s; thereafter, surface warming, cloud-induced changes in solar radiation, and other fields such as wind speed and humidity also became important.

Another important aspect to consider is whether, in the future, the percentage of the area of the islands affected by drought will be greater than in the recent past. In this case, a gridpoint, for a given month, is considered to be in a drought situation if the SPEI index is below -1 . The average percentage of the area under drought conditions is calculated as the mean for all months of the considered period. Again, the reported results are calculated, in turn, as the average of the three simulations for a given period and emission scenario driven by the different GCMs. Table 1 shows the projected changes for 3- and 12-month time scales in the four altitude levels analyzed. Since the recent past (1980–2009) is taken as the baseline, the spatial extent in this period is approximately 15.9% (threshold: $\text{SPEI} < -1$). At all altitude levels, the percentage area affected by hydrological drought (12-month accumulated) is estimated to be greater, between 12 and 17 percentage points (pp), than that affected by meteorological drought.

All changes increase with elevation. For instance, the affected area by hydrological drought in the high emissions scenario,

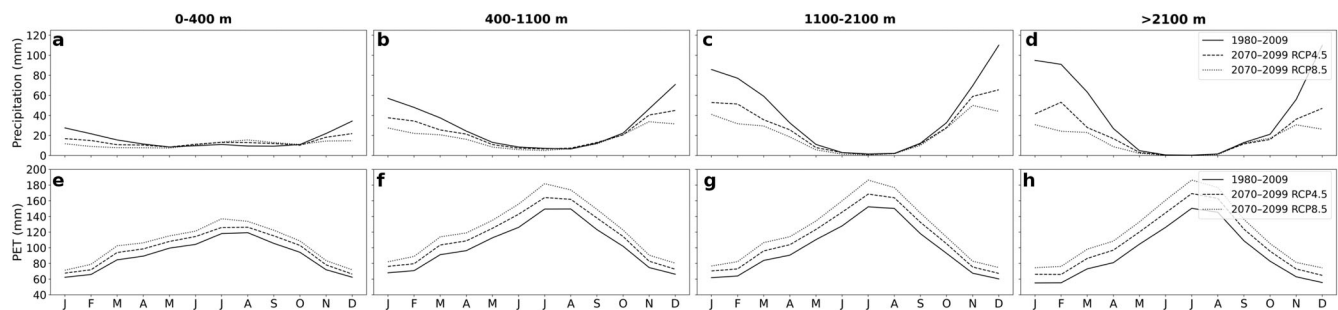


Fig. 4 Annual precipitation and evapotranspiration cycle for recent past and future projections by altitude levels. **a–d** Annual cycle in precipitation (mm) and **e–h** potential evapotranspiration (PET mm), for 30-year period simulations: recent past (1980–2009) and future (2070–2099), scenarios RCP4.5 and 8.5, at the four altitude intervals analyzed.

Table 1. Changes (percentage points, pp) in area affected by drought ($\text{SPEI} < -1$) by altitude intervals, in the future period (2070–2099), under RCPs 4.5 and RCP8.5, relative to the baseline (1980–2009).

Altitude (m)	3 months		12 months	
	2070–2099 RCP4.5	2070–2099 RCP8.5	2070–2099 RCP4.5	2070–2099 RCP8.5
0–400	37	60	54	74
400–1100	42	64	57	77
1100–2100	43	64	56	76
>2100	51	68	65	80

By definition, the affected area in the reference period is 15.9%. Increases have been calculated based on SPEI index computed at 3- and 12-month time scales. All are statistically significant, $p < 0.05$.

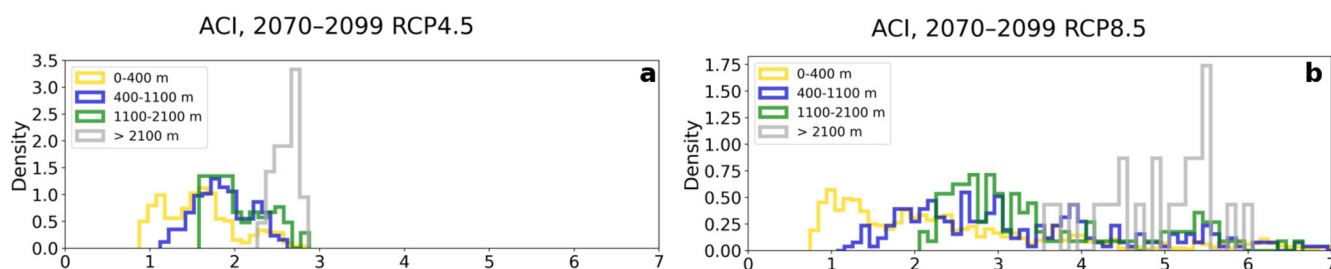


Fig. 5 Distribution of future changes in aridity, by altitude level, in the two scenarios analyzed. Aridity Change Index (ACI) for 2070–2099 RCP4.5 (a) and RCP8.5 (b) expressed as histograms. The altitude levels are indicated in the legend of histograms.

projected for heights below 400 m, would increase by 74 pp compared to the recent past period, while above 2100 m, it would increase by 80 pp. Bearing in mind that, by definition, the area affected in the recent past is 15.9%, an increase of 80 pp implies that almost the entire area in the upper levels would be affected by hydrological drought by the end of the twenty-first century, in the worst-case scenario. On the other hand, the projected change in spatial extent at the two intermediate altitude levels: 400–1100 and 1100–2100 m are very similar, differing by only 1% in the two time scales and emissions scenarios analyzed.

As expected, increasing greenhouse gas concentrations in the atmosphere expands the area affected by drought. In the RCP8.5 scenario, the percentage of surface affected is projected to be larger than in RCP4.5, approximately 20 pp. However, even in the intermediate emissions scenario, the area affected by hydrological drought is noticeable, reaching an increment of 65 pp in the higher elevations of the islands. Statistical robustness of the simulated changes was evaluated with the bootstrapping technique (see Methods section) and all changes were significant at a 95% confidence level.

The general decrease in future precipitation, mainly in the highest areas of the islands, along with an increase in evapotranspiration, also leads to an expected rise in aridity. The ACI index has been calculated for the last three decades of the century, for each emissions scenario, relative to the recent past. The computation was performed for each land gridpoint, averaging the results for the three simulations driven by the different GCMs. Figure 5 shows the ACI histograms for the different elevation bands selected. In scenario RCP4.5, ACI ranges, on average, from 1.6 below 400 m to 2.6, at levels above 2100 m, and from 2.6 at the lowest altitude levels, up to 4.9 in the highest ones, in the RCP8.5 scenario. At high levels, represented in gray color in the histograms, an aridity index of up to 6 can be reached. Once more, an enhanced effect of climate change on aridity can be observed with elevation. A previous study¹¹, based only on GCM data, determined an ACI around 1.1 at mid-century and 1.4 at the end of the century for the Canary Islands in RCP8.5. However, GCMs do not represent the island topography well due to their low spatial resolution, which plays a major role in precipitation. As an example, only one of the three GCMs used in this study, GFDL, considers a maximum elevation greater than zero in the region in which the archipelago is located, only 25 masl. The regional simulations performed in the present study, although also limited by the discretization of the topography, consider a maximum height of about 3000 masl.

Spatial distribution of projected changes in drought and aridity

In previous sections, the dependence of the expected changes in altitude has been analyzed, considering four altitude ranges. However, the relief of the islands causes the climate in different areas of an island to be highly uneven, as well as changes in the future. The results of several indices related to drought and aridity

will be presented below in the form of maps to facilitate the interpretation of such variability.

Future changes in the drought events at the end of the twenty-first century (2070–2099), under the two emissions scenarios, relative to the reference period (1980–2009), for the SPEI index computed at 3- and 12-month time scales, are presented in Figs. 6 and 7, respectively. These are categorized by frequency, duration, and severity. The results correspond to the average of the simulations driven by the three GCMs. The changes are considered to be robust at a given gridpoint if the three changes are of the same sign (see methodology).

Drought events, in the 3-month time scale (Fig. 6), occur between 16 and 24 times in the 30-year period 1980–2009, with an average duration of between 4 and 6.5 months, and severity rating from -1.4 to -1.7 (1st column, Fig. 6). In the WRF simulations corresponding to both emissions scenarios, in the northern part of the islands the frequency could increase by 10 more events during the future period but would decrease by 20 events in the south and east of the western islands. The decrease in the number of events in many areas is associated with an increase in event duration, which for RCP8.5 increases dramatically up to around 250 months. In general, in the areas where the number of drought events increases, severity increases to a lesser degree. However, in the rest of the areas, the events reach, on average, the maximum drought severity values, which have been set to -3 .

In the recent past, on the 12-month time scale (Fig. 7), the drought events are, as expected, less frequent (from 5 to 9 events) and of longer duration (between 15 and 25 months) than those computed from SPEI3. Although their severity is similar to the 3-month time scale analysis, projections at the end of the century of SPEI12 were revealed to be even more severe in the intermediate scenario and with a widespread increase in the duration, up to 300 months over a simulated 360-month period, than those of the SPEI3 index.

Practically through the entire territory, whether meteorological or hydrological drought is analyzed, the severity values reach extremes. That is, if the drought events of the recent past have an average value of -1.5 , adding the expected changes of up to -1.5 , extreme values would be reached even in the intermediate emissions scenario, RCP4.5.

These same simulations, using the SPI index (see Supplementary Figs. 2 and 3), projected a further decrease in the number of events and their duration. They also produce less severe results than for the SPEI in most of the territory, in the two accumulations (3 and 12 months) analyzed. A decline in hydrological drought is even observed in some areas of Lanzarote and Fuerteventura, the two easternmost islands, if only precipitation is taken into account. As mentioned before, in the Canary Islands, evapotranspiration plays a major role in drought. By including it in the calculation, drought will generally be more frequent, longer, and more severe. Previous analyses have also highlighted the need to include temperature to study potential changes in the conditions of semi-arid regions, such as the Iberian Peninsula²⁸, Australia²⁷, or

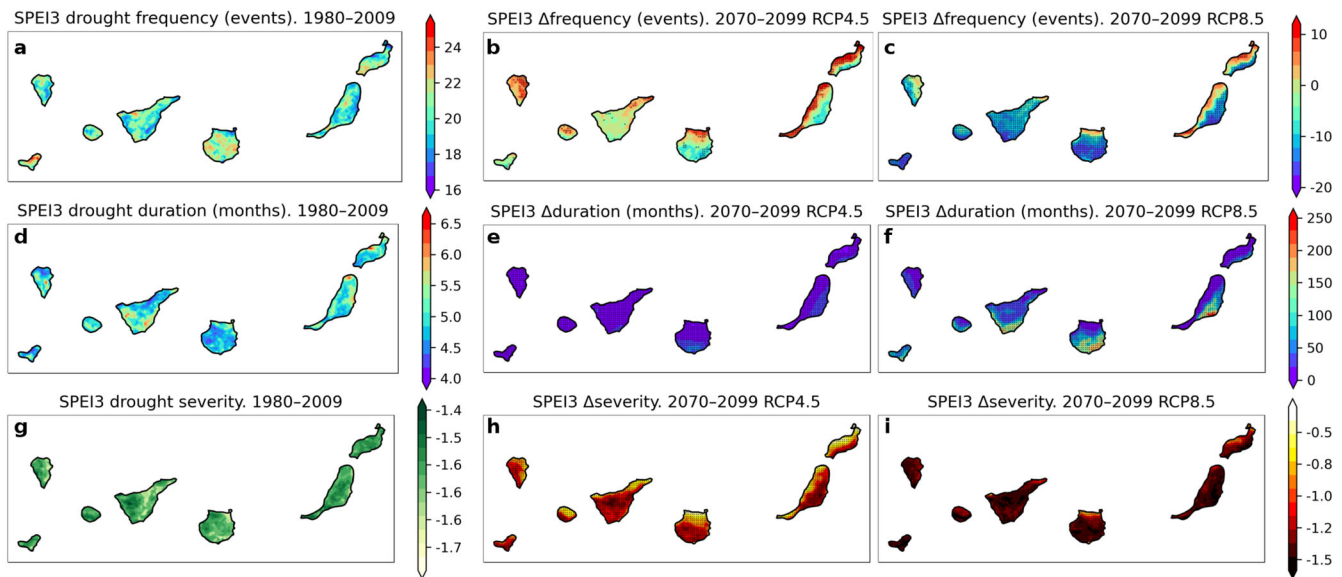


Fig. 6 Meteorological drought frequency, duration and severity in the recent past and their projected changes. Drought frequency (number of drought events in 30 years) (a–c), duration (months) (d–f), and severity (SPEI rating) (g–i) for the SPEI index computed at a 3-month time scale. Changes in the frequency, duration, and severity of drought events for the future (2070–2099), under RCP4.5 (b, e, h) and RCP8.5 (c, f, i), relative to the recent past period (1980–2009) (a, d, g). Duration and severity were obtained from values averaged for the entire period, whereas frequency is the number of events in 30 years. Dotted gridpoints correspond to robust future changes.

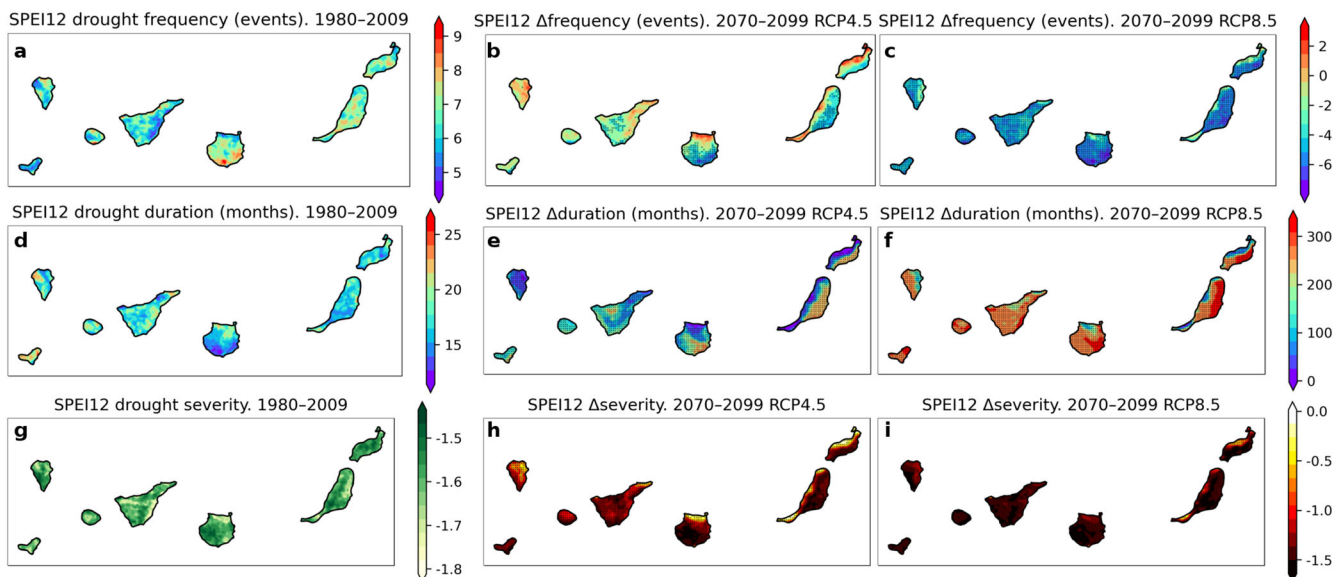


Fig. 7 Hydrological drought frequency, duration and severity in the recent past and their projected changes. Drought frequency (number of drought events in 30 years) (a–c), duration (months) (d–f), and severity (SPEI rating) (g–i) for the SPEI index computed at a 12-month time scale. Changes in the frequency, duration, and severity of drought events for the future (2070–2099), under RCP4.5 (b, e, h) and RCP8.5 (c, f, i), relative to the recent past period (1980–2009) (a, d, g). Duration and severity were obtained from values averaged for the entire period, whereas frequency is the number of events in 30 years. Dotted gridpoints correspond to robust future changes.

California²⁹. A similar result with the role of temperature is shown by Herrera et al. for the Caribbean Islands for historical droughts³².

Figure 8 shows the ACI for the two future projections, with the two emissions scenarios. Given the results presented so far, an increase in aridity is expected, being more noticeable in the case of RCP8.5. The changes are less severe in the eastern islands, Lanzarote and Fuerteventura, which are already quite arid at present, as rainfall is very scarce on them. The areas where simulations project the greatest change in aridity are the southeastern slopes of the two central islands, Tenerife and Gran Canaria. The marked increase in aridity in these areas is mainly due to a decrease in precipitation (see Supplementary Fig. 4).

DISCUSSION

Improving our understanding of the parameters affecting drought, the relationship between them, and their future projections are necessary in order to develop measures to reduce its impacts¹. Drought is a complex phenomenon that models indicate will be accentuated in the Canary Islands with climate change. Climate projections of drought and aridity, both spatially and seasonally, have been analyzed at the end of the twenty-first century. In general, droughts will be considerably longer and more severe, worsening significantly with altitude.

In the analysis of meteorological droughts, the inclusion of evapotranspiration has been essential. Not including it in arid

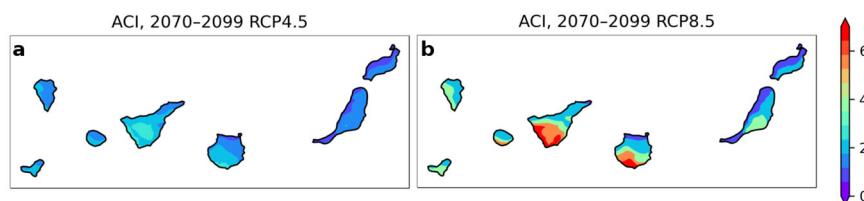


Fig. 8 Maps of future changes in aridity for the two scenarios analyzed. Aridity Change Index (ACI) for 2070–2099 RCP4.5 (a) and RCP8.5 (b). All three models coincide in a positive change of ACI at all gridpoints.

regions, such as the Canary Islands, could lead to erroneous conclusions of reduced drought in the face of very small increases in precipitation projections, which will be largely exceeded by the expected increase in evapotranspiration. The season with the most severe projected droughts is autumn, which may affect crop planting or reforestation management. An increase in the meteorological drought index is also expected during the spring, affecting the growing season that can severely reduce crop yield³³.

Drought undoubtedly has a socio-economic impact on two vital sectors of the Canary Islands: tourism and agriculture, as well as on their ecosystems. In addition, periods of drought increase the negative impacts of some hazards, such as fires. Particularly in the eastern islands, tourism development has boosted the installation of seawater desalination plants, despite the associated economic costs related to energy demand. Desalination plants may continue to help mitigate the effects of drought on economic sectors, at the cost of lower profitability, but ecosystems are more vulnerable to this hazard. Furthermore, previous studies have highlighted the importance of horizontal rainfall in the maintenance of forests, especially during the summer months. The yearly average water contribution to the soil surface by wind-driven fogs, measured in the forest area of the island of La Gomera, was 251–281 mm, whereas annual rainfall was between 635 and 1088 mm³⁴. In addition, the occurrence of clouds on windward slopes also helps to limit evapotranspiration. This aspect has not been analyzed in this study and future projections should analyze whether climate change will affect the frequency, height, and strength of the stratocumulus. The inclusion of water demand for each of the islands would also be of great interest to estimate the impact of the projected changes¹.

Despite the elevated computational cost, the raised dependence of drought changes on elevation demonstrates that the high spatial resolution climate projections are a requirement to conveniently simulate complex rainfall patterns and microclimates. For example, processes related to the ocean-land interface or the orientation of slopes, upwind or downwind of the prevailing trade winds, also have a significant influence on projected changes in drought. Previous studies¹¹ had calculated an aridity index, in the Canary Islands, of up to 1.5, and it was identified as one of the archipelagos most affected by the increase in aridity. However, in the simulations performed in this work, the increase in spatial resolution has allowed us to compute the ACI for each altitude interval. The drought projections significantly worsen up to an aridity index of 6, for the highest elevations in the worst-case scenario. Although general trends are in concordance, this difference in magnitudes may be due to the insufficient spatial resolution in these previous studies for the case of the Canary Islands. Land surfaces tend to warm more rapidly than the ocean, implying that the low spatial resolution can lead to conservative estimates of PET increase, and also ignores changes in orographic precipitation.

METHODS

Drought and aridity indices

Drought occurs due to the deficiency of water resources. Drought indices are defined to standardize the average situation at each

point, and thus to calculate drought events in terms of precipitation (P) deficit, SPI index, or precipitation minus potential evapotranspiration (P-PET), SPEI index⁹. In this work, both indices were obtained at two different time scales: 3 months to detect meteorological droughts and 12 months to identify hydrological droughts^{35–37}. In both cases, the corresponding monthly time series, for P or P-PET, were computed using the previous n months, where n is the selected time scale. The indices were calculated by fitting a probability density function to the frequency distribution of the values of the series and then transforming the obtained function into the standardized normal function. In this way, the indices were normalized for a given location and time interval. For comparative purposes, both indices were fitted to a log-logistic probability distribution based on unbiased Probability Weighted Moments using the robust L-moments procedure³⁸. This methodology ensures that both SPI and SPEI indices are comparable and the differences will be the result of evapotranspiration effects³⁹. Calculations were based on the SPEI R package (<https://cran.r-project.org/package=SPEI>). A relative approach has been used³⁹, obtaining the parameters of the distribution by considering only the series of the recent past and then obtaining the drought indices of each period, past or future, concerning these parameters. This facilitates the interpretation of possible changes in different future periods and/or under different greenhouse gas concentration pathways.

The Penman–Monteith (PM) method^{40,41}, which is recommended by the Food and Agriculture Organization and WMO, and widely used for studies of transient climate change^{42–44}, was selected to calculate PET. Other PET calculation methods were also tested for the time series of several WMO stations located in the study region, but the results were quite different from those provided by PM and also by the previous studies⁴⁴. Due to this, their use was not considered appropriate.

Drought is characterized by a temporal anomaly concerning long-term average conditions¹. According to the dryness/wetness classification by McKee et al.⁵ (see Supplementary Table 1), in every gridpoint, a drought event is established when dry conditions start (SPEI or SPI indices below -1 , which translates into values of P-PET or P below the percentile 15.9th, in the corresponding standardized normal distribution). The end of the event is determined when normal conditions are recovered again, after a minimum period of 2 months⁴⁵ (value 0 in the SPEI or SPI indices, corresponding to the 50th percentile of the reference period in P-PET or P)⁴⁶. The minimum/maximum values of SPI and SPEI have been limited to $-3/3$, which corresponds to the 0.1th percentile of the reference period. As customary, values below -2 (2.3th percentile) are considered “extreme drought”⁵.

Projected changes in droughts were analyzed in terms of duration, frequency, severity, and spatial extent affected by drought. Following other studies^{47–49}, duration is defined as the consecutive number of months of a drought event; frequency is the number of drought events during the 30 years study period (1980–2009 or 2070–2099); severity indicates the magnitude of each event and is computed as the minimum index reached during it. The spatial extent of drought is measured as the

Table 2. CMIP5 GCMs used as initial and boundary conditions in the downscaling experiments.

GCM name	Institution	Resolution	Reference
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, USA	2.5 × 2	⁶¹
IPSL-CM5A-MR	Institut Pierre Simon Laplace, France	2.5 × 1.25	⁶²
MIROC-ESM	The University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	2.8 × 2.8	⁶³

percentage of land gridpoints in which the drought index falls below the threshold -1 .

To assess aridity in the islands, the ACI was computed as proposed in a previous study¹¹. ACI is defined as the ratio of the fractional change in PET to the fractional change in precipitation (P): $ACI = (PET_F/PET_{RP}) / (P_F/P_{RP})$ where subscript F and RP indicate future and recent past, respectively. The future periods correspond with 2070–2099, and the recent past with 1980–2009. In this case, future wetter conditions are considered when $ACI < 1$ and drier conditions when $ACI > 1$, if $ACI \approx 1$, there are no projected aridity changes.

Model setup

Regional climate simulations have been accomplished with the non-hydrostatic WRF model (WRF/ARW, v3.4.1) using a one-way triple nesting setup, reaching a grid resolution of 3×3 km. The WRF version and the physical parameterizations were performed following previous studies in the same area^{20,50}. The selected physics schemes were the WRF double-moment 6-class⁵¹ micro-physics scheme, the Yonsei University planetary boundary layer scheme⁵², the Noah land surface model⁵³ and the Community Atmosphere Model version 3 scheme⁵⁴, for both longwave and shortwave radiation. The Kain–Fritsch scheme⁵⁵ was selected for cumulus parameterization, being switched off in the innermost domain. The vertical resolution consisted of 32 vertical levels unevenly distributed, mainly concentrated close to the surface.

Lateral and boundary conditions to drive the RCM simulations have been obtained from three GCMs participating in the CMIP5 project (Table 2), using the r1i1p1 realization in each case. As habitual in long-term climate studies, simulations started one year before the target period to reduce the physical inconsistencies introduced by the mismatch between the low-resolution GCM initial conditions and RCM high resolution, so this first year was excluded from the analysis⁵⁶.

Bias correction

Despite the progressive increase in the complexity of RCMs and in the spatial resolution of simulations, results are often affected by bias, which can be estimated by comparing them with observational data⁵⁷. These errors are partly inherited from the driving GCMs. For this reason, especially in results relevant to impact studies, a method of bias adjustment should be applied. Specifically, a trend-preserving parametric bias adjustment method, the Scaled Distribution Mapping (SDM) algorithm⁵⁸, has been used in this study. In particular, the code for SDM was obtained from the Python pyCAT package (<https://github.com/wegener-center/pyCAT>). The results of a WRF simulation driven by Era-Interim data from a previous study²⁰ were taken as the reference data to adjust the bias of the simulations driven by GCMs in both the recent past and future periods. A similar

procedure was successfully applied in previous work in the same region²⁴. To avoid discontinuities at the transition between months, bias adjustment was applied to the central calendar month of a sliding 3-month window for each land gridpoint.

Robustness tests

To evaluate projected changes, two different periods have been simulated: the recent past (1980–2009), and the end of the century (2070–2099). In the future period, two different greenhouse gas concentration pathways (RCP4.5 and RCP8.5), representing middle and high emission assumptions¹⁵, were used. At each gridpoint, the future changes in drought events parameters, frequency, duration, and severity, are considered to be robust if the projected changes obtained from simulations driven by the three GCMs (GFDL, IPSL, MIROC) have the same sign (all positive or all negative).

To verify that the changes in the mean future values are statistically significant, the monthly time series of the analyzed parameters were calculated for each gridpoint. For those indices calculated for a height range, the time series correspond to the monthly means of the spatial averages. The one-tailed null hypothesis H_0 of no difference or negative change in each of those points was tested. Since we cannot guarantee that each of the samples to be compared belongs to a normal distribution or other parametric distribution, or that they have a similar spread, a bootstrap procedure was applied⁵⁹ to the corresponding recent past and future series. A set of 1000 bootstrap samples was generated using random re-sampling with replacement. The future changes are considered to be significant if p value < 0.05 .

Observational data

The simulated parameters used to calculate drought, precipitation, and PET, have been validated with observational station databases from ECA&D⁶⁰ in the study region. This dataset consists of daily temperature, precipitation, wind speed, and cloud cover series for the recent past period (1980–2009).

This study has focused on the impact of altitude on drought. For this purpose, four altitude intervals have been analyzed, based on previous studies of thermotypes²⁵: 0–400 m (849 gridpoints), 400–1100 m (256 gridpoints), 1100–2100 m (113 gridpoints), >2100 m (24 gridpoints). To validate that the model reproduces the mean values and seasonal variation correctly, precipitation and evapotranspiration, variables with which all drought indices have been calculated, were evaluated for three locations representative of different heights on the island of Tenerife: SCT (46 m), TFN (632 m) and IZA (2371 m) (Supplementary Fig. 5).

DATA AVAILABILITY

The CMIP5 GCM results are publicly available on Earth System Grid Federation (ESGF) facilities and on Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre (DDC). Results of WRF regional simulations for the Canary Islands are available on request from the authors.

CODE AVAILABILITY

Codes to produce the figures and tables are available from the corresponding author.

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Conceptualization: J.C., S.H.-B., A.G., and J.P.D. Methodology: J.C., S.H.-B., A.G., F.J.E. Software: J.C.P. Data curation: A.G. and J.C.P. Validation: J.C., S.H.-B., A.G., and J.C.P. Analysis: J.C., F.J.E., and J.P.D. Writing—original draft: J.C., A.G., J.C.P., F.J.E. and J.P.D. Project administration: J.P.D.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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