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ORIGINAL ARTICLE

Projected impacts of climate change on tourism in the Canary Islands

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Abstract

The Canary Islands are a leading tourist destination. Their strong economic dependence on this sector makes them vulnerable to climate change. The steep orography of the islands causes impact of climate change and their potential influence on tourism to be spatially heterogenous. To account for this variability, regional climate simulations were computed using the Weather Research and Forecast (WRF) numerical weather prediction model driven by the results of three CMIP5 global climate models as boundary conditions, using two different future greenhouse gas emission scenarios (RCP4.5 and RCP8.5) for the projections. The simulations were performed at a spatial resolution of 3 km for three 30-year periods, recent past (1980–2009), mid-century (2030–2059), and end-century (2070–2099). For two widely used indices of tourist attractiveness (the Tourism Climate Index TCI and the Holiday Climate Index HCI), the coastal region of most islands currently has between 20 and 30 “excellent” and “ideal” days per month for tourism, with a decrease at higher elevations. Future leisure conditions are expected to improve at higher locations and during the autumn, winter and spring. In the RCP8.5 scenario, “excellent” days are projected to increase in winter at the end of the century. Nevertheless, in the southern areas, where most of the hotel infrastructure is located, the indices indicate significantly worsened conditions in summer, with only a few “excellent” days expected in some locations. Thermal comfort was identified as the most important factor determining the expected changes.

Keywords Tourism · Climate change · Canary Islands · Tourism indices · Regional climate projections

Introduction

The sun and the beach were the most popular reasons given (42%) for going on holiday in the Eurobarometer Preferences of Europeans towards tourism, published in March 2016 (Eurobarometer 2016). The weather determines tourist comfort, and the best schedule for many activities which can be done during the holidays, for example, those related to nature (mountain, lake, landscape, etc.), city trips or sports and also facets of operations (water supply, cooling costs, irrigation needs, etc.) (Scott and Lemieux 2010). Therefore, the tourism industry is considered highly vulnerable to climate change (Scott et al. 2012; Gómez-Martín et al. 2020), even more than the overall economy (Dogru et al. 2019). Thus, it has been identified as the number one challenge to tourism along the twenty-first century (Higham and Hall 2005; Scott et al. 2008). For many small islands, in the Caribbean and Mediterranean Sea, and the Indian and Pacific Ocean, climate change constitutes a threat to their tourism-dependent economies (Uyarra et al. 2005; Dodds and Kelman 2008; Klint et al. 2012; Scott et al. 2019; Douglass and Cooper 2020). However, studies of future projections of the climatic conditions for tourism are scarce in these territories.

Tourism is fundamental to the economy of the Canary Islands, where 40% of employment is dependent on the tourism sector and contributes 35% of gross domestic product (GDP). In 2018, the islands had a population of 2.2 million people and received an influx of 13.8 million foreign tourists (Simancas Cruz et al. 2020). Contrary to other tourist destinations, seasonal fluctuations in tourist demand are very small. The results of surveys carried out by the Government of the Canary Islands to visiting tourists

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(see Supplementary Material) show that almost 90% of them state that the main reason for choosing the islands is the climate or the sun. Despite the importance of this sector and the increase in the number of studies carried out on climate change and tourism in recent years (Fang et al. 2018), in previous studies on the impact of climate change on tourism in Europe (Amelung and Moreno 2009; Perch-Nielsen et al. 2010; Grillakis et al. 2016; Jacob et al. 2018; Sesana et al. 2018) or Spain (Hein et al. 2009; Olcina Cantos and Vera-Rebollo 2016; Toimil et al. 2018; Torres-Bagur et al. 2019), there were no tourism projections available to the Archipelago. Previous studies in the Canary Islands have focused on historical analysis (Garín-Mun 2006; Perez-Rodríguez et al. 2015; Alonso-Pérez et al. 2021; Inchausti-Sintes et al. 2021). Future projections of some general climate variables have been also studied (Expósito et al. 2015) using the pseudo-global warming technique, which cannot adequately capture potential changes in the variability from daily to interannual time scales.

Numerical climate models

Numerical models and observations have become indispensable tools to achieve a better understanding of our climate system, not only to understand and forecast the weather but also to evaluate the impacts of climate change (Knutti and Sedláček 2013). Over recent years, the Coupled Model Intercomparison Project (CMIP) (Taylor et al. 2012), under the auspices of the World Climate Research Programme (WCRP), has developed climate change projections throughout the twenty-first century. Results from these simulations have been used by The Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013; Hoegh-Guldberg et al. 2018) to provide policymakers with regular scientific assessments on climate change, its implications, and potential future risks.

However, due to the spatial resolution of these global climate models, around a hundred kilometers, they are not able to provide the regional climate information at the necessary high resolution required by researchers, stakeholders, and policymakers, especially in regions with complex orography or in coastal areas (Leung et al. 2003). To obtain this detailed information dynamical downscaling techniques have been widely used, in which global climate models (GCMs) data are used as the lateral boundary conditions for regional climate models (RCMs) (Giorgi and Gutowski 2015). With better resolved characteristics, such as surface topography, vegetation, and land-sea distributions, RCMs are more capable of reproducing climate features in these regions (Arritt and Rummukainen 2011; Giorgi and Bates 1989; Rummukainen 2010).

Tourism climate indices

The impact of climate on tourism has been analyzed using indices based on various components: thermal comfort (air temperature, humidity), aesthetic (sunshine/cloudiness), and physical (wind, rain, ...) (Scott et al. 2012), which endeavor to express, in a single index, climate conditions for tourism. The indices include the following atmospheric parameters: temperature, humidity, precipitation, sunshine/cloudiness, and wind speed, which have different weights depending on the planned tourist activities: general, beach, urban, etc. Temperature and humidity are usually combined to calculate a measure of human thermal comfort. Nonetheless, thermal comfort of individual tourists cannot be entirely explained by the energy balance of the human body. They are also affected by psychological and behavioral factors, countries of origin, etc. (Lin and Matzarakis 2008; Lin et al. 2011).

Despite the aforementioned uncertainties in the definition of the indices, previous studies have measured a high correspondence between tourist indices and the number of overnight stays in different destinations (Amelung and Moreno 2009; Rosselló-Nadal 2014), proving to be an effective general measure of the climate suitability of destinations. The widest used index is the Mieczkowski Tourism Climate Index (TCI) (Mieczkowski 1985). Subsequently, the Holiday Climate Index (HCI) was formulated to assess the climatic suitability of destinations for tourism (Tang 2013; Scott et al. 2016); this index can be segmented into destination types (e.g., beach, urban). The TCI approach has been used to study the impact that climate change might have on tourism patterns in North America (Scott et al. 2004) and included as an independent variable in a tourism demand model (Goh 2012). However, several studies demonstrate that HCI overcomes some TCI deficiencies, showing better consistency with visitation patterns observed in different urban and beach destinations (Scott et al. 2016; Rutty et al. 2020).

This study will focus on climate projections for the Canary Islands and their impact on tourism, using the above-mentioned indices computed from multi-model multi-scenario climate simulations with a high spatial resolution (3 km). However, for a global vision of the impact of climate change on tourism, stakeholders should also take into account studies carried out in tourist-sending regions. Moreover, adaptation solutions to climate change must be developed on the basis of inter- and trans-disciplinary cooperation. For example, adapting public spaces to climate change requires the simultaneous contribution of climatic, ecological, design, sociological and economic aspects (Foshag et al. 2020). The objectives of the paper are twofold.

First, to provide a high-resolution analysis to partially overcome the scarcity of climate projections on tourism in small islands and, second, to provide stakeholders with the estimations of improvement or worsening in the indices, by location and season, as a starting point in the development of adaptation strategies to climate change. Nonetheless, the generation and study of climatic relevant data are the first step in order to be able to carry out any subsequent study.

Methodology and data

Study area

The Canarian archipelago is located in the North Atlantic subtropical region, close to the African coast (Fig. 1). From a climatological point of view, the Canary Islands are under the influence of the Azores High and the cold Canary Current. These factors make the climate stable throughout the year, which is also strongly conditioned by the complex orography. The mean annual air temperature, in the areas located at sea level in the Canary Islands, where the main tourist activities are currently located, vary from 20 to 21 °C, pleasant temperatures with an annual thermal amplitude in the order of 6 to 7 °C. Mean temperatures drop to below 4°C at the peak of Mount Teide on the island of Tenerife, at 3700 meters above sea level.

Climate in this area is characterized by a vertical stratification in the Troposphere due to an almost permanent stable thermal inversion layer (Carrillo et al. 2016), which avoids the vertical movements of the air masses, conditioning the rain regime. Average monthly rainfall varies throughout the year, with notable seasonality. The rainiest months in the whole of the Canarian archipelago are December and January. During these months, in the highest areas of the center of the island of La Palma (usually above the thermal inversion), the average monthly precipitation exceeds 200 mm, while on the contrary, in the coastal areas of the south of Tenerife and Gran Canaria and the east of Fuerteventura are below 20 mm (Chazarra et al. 2012).

Climate indices for tourism

TCI index is widely used to quantify the climate suitability of outdoor tourist destinations (Mieczkowski 1985), based on monthly mean climatic data. The literature has discussed its subjectiveness (Scott et al. 2016; Rutty et al. 2020; Rutty et al. 2021); however, its calculation is useful for intercomparison with previous studies executed in other tourist destinations. It consists of four sub-indices (see Eq. 1). (1st) Thermal Comfort (TC): Daytime Comfort Index CID (a function of maximum daily temperature, °C, and minimum daily relative humidity, %) and Daily Comfort Index CIA (depending on mean daily temperature, °C and mean daily relative humidity %); (2nd) Precipitation, R: which depends on total precipitation, in mm; (3rd) Sunshine, A: defined as a function of total hours of sunshine; and (4th) Wind, W: a sub-index related to the daily average wind speed, in km/h. All of which are calculated in their specific units and then rated on a scale. The index is calculated as follows:

$$TCI = 2(TC) + 4(R) + 4(A) + 2(W) \tag{1}$$

where $TC = 4(CID) + (CIA)$.

All sub-indices are calculated by assigning a rate depending on ranges in monthly values, the optimal score for each variable is 5 (Mieczkowski 1985; Amelung and Moreno 2009). For example, a rating of 100 in TCI is achieved with the following "ideal" conditions: effective temperature between 20 and 27 °C, average monthly precipitation below 15 mm/month, average monthly sunshine greater than 10 hours per day and wind speed less than 2.88 km/h. These conditions imply a rating value of 5 in each sub-index, which corresponds to TCI = 100. On the contrary, a rating value of 0 in TCI would be reached with the following extreme values: Effective temperature between −10 and −5 °C (lower values would even imply a negative rating in TCI), average monthly rainfall greater than 150.0 mm/month, average monthly sunshine less than 1 hour/day, and wind speed greater than 38.52 km/h. TCI values below 10 are considered as "impossible" in the comfort level for tourism activity.

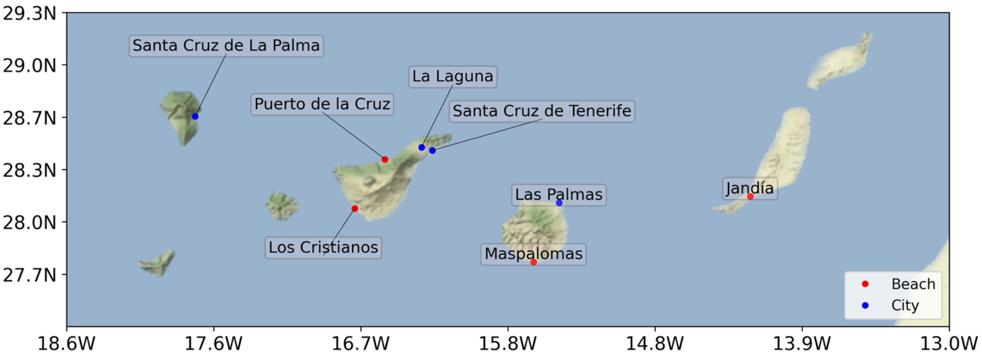

Fig. 1 Location and topography of the Canary Islands. Distribution of beach and city tourist areas analyzed in this work

Due to the weighting scheme limitations of TCI, with an overemphasis on thermal comfort (Dubois et al. 2016), the HCI index was developed, which allows the segmentation of destination types (i.e., beach or urban) (Tang 2013; Scott et al. 2016), establishing a specific index according to the holiday target. The HCI Beach index (HCIB) (2) and the HCI Urban index (HCIU) (3) are computed from four terms that are related to different climatic variables: (1st) Thermal Comfort (TC), which is a combination of daily maximum temperature, °C, and mean relative humidity, %; (2nd) Aesthetic A: related to cloud cover, %; (3rd) Precipitation R, mm, and (4th) Wind speed W, km/h:

$$HCIB = 2(TC) + 4(A) + 3(R) + (W) \tag{2}$$

$$HCIU = 4(TC) + 2(A) + 3(R) + (W) \tag{3}$$

Considering that 34.5% of tourists (not segmented) have answered “beach” as a reason for traveling to the Canary Islands (see Supplementary Material), the HCIB index projections have socio-economic relevance. The HCIU index performs the analysis of climate suitability for other tourist activities in which cloud cover is of less importance than thermal comfort.

Each climatic variable is rated on a scale of 0 to 10, with an overall HCI index ranging from 0 (potentially “dangerous” for tourists) to 100 (“ideal” for tourism). In both cases, HCI and TCI, they are considered “ideal” for values above 90 and “excellent” from 80 to 89 (a summary of the descriptive ranges is included in Supplementary Material). In this study, the indices used to assess the suitability of this destination are TCI80 (TCI $>$ 80), HCIB80 (HCIB $>$ 80) and HCIU80 (HCIU $>$ 80): the number of “excellent” or “ideal” days for a specified period.

Model setup

Regional climate simulations have been performed with the non-hydrostatic Weather Research and Forecasting (WRF) model (WRF/ARW, v3.4.1) using a one-way triple nesting setup with grid resolutions of 27 km × 27 km, 9 km × 9 km and 3 km × 3 km. The coarse outer domain, centered in the north-eastern Atlantic, covers a wide region to capture the main mesoscale processes that affect the Canarian climate, while the two innermost domains are centered in the Canarian archipelago.

The WRF version and the physical parameterizations used to represent the different sub-grid scale atmospheric processes were selected according to previous studies in the same area (Expósito et al. 2015; Pérez et al. 2014). So, the selected physics schemes were the WRF double-moment 6-class (WDM6) (Lim and Hong 2010) microphysics scheme, the Yonsei University planetary boundary layer scheme (Hong et al. 2006), the Noah land surface model (Chen and Dudhia 2001) and the Community Atmosphere Model version 3 scheme (Collins et al. 2004), for both longwave and shortwave radiation. Concerning cumulus parameterization, the Kain-Fritsch scheme was used, but it was switched off in the innermost domain. The vertical resolution follows the same configuration as in Pérez et al. (2014) and Expósito et al. (2015), with 32 vertical levels unevenly distributed, mainly concentrated in the lower part of the atmosphere.

Boundary conditions that drive the RCM simulations have been obtained from three GCMs participating in the CMIP5 project and whose main characteristics are summarized in Table 1. In all cases, only the realization r1i1p1 was used in the downscaling process. To evaluate projected changes, three different periods have been simulated: recent past (1980–2009), mid-century (2030–2059), and end of the twenty-first century (2070–2099). Simulations started one year before the target period to reduce the physical inconsistencies introduced by the discrepancy between the low-resolution GCM initial conditions and the RCM’s high resolution, so this year was excluded from the analysis. For the future periods, two different greenhouse gas concentration pathways, the CMIP5 representative concentration pathway 4.5 and 8.5 (RCP4.5 and RCP8.5) scenarios were used. These scenarios

Table 1 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°	(Dunne et al. 2012)
IPSL-CM5A-MR	Institut Pierre Simon Laplace, France	2.5° × 1.25°	(Dufresne et al. 2013)
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°	(Watanabe et al. 2011)

represent middle and high emission assumptions, using emission pathways that lead to the stabilization of radiative forcing at 4.5 and 8.5 Wm^{-2} at the end of this century, respectively (van Vuuren et al. 2011).

Statistical methods

TCI80, HCIB80, and HCIU80 indices measure the proportion of days that are "excellent" and "ideal" for tourism for a defined period, in this case, a month. To analyze the statistical significance of the future changes, the Chi-squared test has been selected as the most appropriate to analyze the statistical significance of two population proportions (Dibike and Coulibaly 2005; Montgomery and Runger 2014).

Let X_1 and X_2 represent the number of days with tourism indices categorized as "excellent" or "ideal" in the recent past and future periods, respectively, and n_1 and n_2 are the total number of days analyzed in the corresponding period. The statistical test, Z, for the null hypothesis, H0: p1=p2, can be expressed as

$$Z_0 = \frac{\hat{P}_1 - \hat{P}_2}{\sqrt{\hat{P}(1-\hat{P})(\frac{1}{n_1} + \frac{1}{n_2})}} \tag{4}$$

Furthermore, the normal approximation to the binomial is assumed for each population, so the estimators of the population proportions $\hat{P}_1 = X_1/n_1$ and $\hat{P}_2 = X_2/n_2$ have an approximately normal distribution. $\hat{P}$ is computed as $(X_1 + X_2)/(n_1 + n_2)$. The alternative hypothesis is H1: $p_1 \neq p_2$.

The test of proportions is applied to each of the future simulations, comparing them with the corresponding recent past simulation, that is, the one driven by the same global model. Additionally, to guarantee the robustness of the results, considering the ensemble of the simulations using different driven GCMs, the criteria followed by previous studies, with the condition that the direction of the changes is uniform (Jacob et al. 2014; Pfeifer et al. 2015), have been considered. The main idea is that the mean climate change signal, computed from a set of climate change simulations, is more robust if most of the simulations agree on the sign of the change. In this study, more restrictive conditions for robustness have been chosen: significance level $\alpha = 0.10$ in the statistical test for changes in a particular future period and RCP, concerning the recent past period, must be achieved by the results in, at least, two corresponding simulations (one for each driven GCM), and all these three simulations must have the same change directions. Regions that pass both tests are identified in the results as robust projected changes.

Results

Before considering future changes, an evaluation of the different indices estimated from the models was performed, comparing them with those obtained from observational

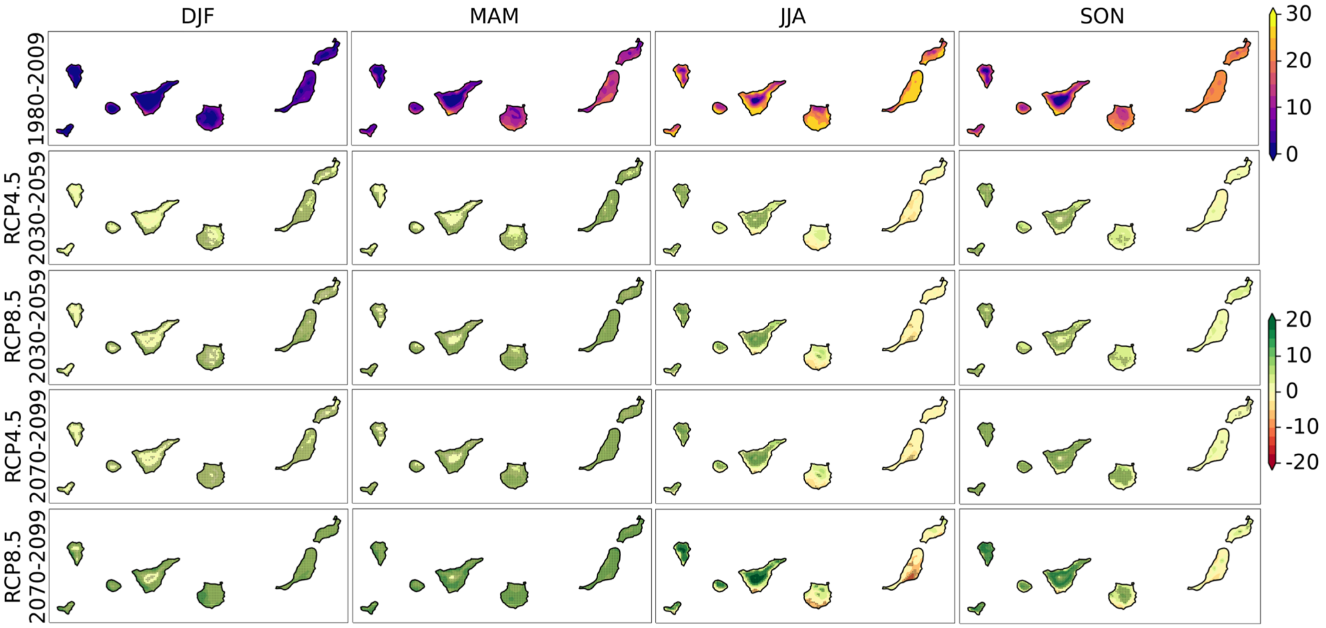

Fig. 2 Projected changes of HCIB80 (days per month) for 2030–2059 (2nd and 3rd rows) and 2070–2099 (4th and 5th rows) compared to 1980–2009 (1st row), for RCP4.5 and RCP8.5 emission scenarios. Data has been seasonally analyzed (columns), including boreal winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Hatched areas indicate robust and statistically significant change

data. This comparison can be found in the Supplementary Material. The biases for the three tourism indices (TCI, HCIB and HCIU) are lower than the statistically significant future variations predicted by the WRF model and the root mean square error (RMSE) is between 2.1 and 8.8%.

Seasonal changes for tourism climatic conditions

Figures 2 and 3 show the seasonal HCIB80 and HCIU80 indices, which correspond to "excellent" days for tourism, for the reference period 1980–2009 and the projected changes for the 2030–2059 and 2070–2099 periods, for both RCP4.5 and RCP8.5 scenarios (see TCI80 index in Supplementary Material).

Under the recent past climatic conditions (1980–2009), the first row in the figures, the coastal areas of the higher islands (western) and most of the flatter islands (eastern) have a high average of "excellent" days for tourism, during the spring, summer and autumn seasons. Even during the winter months, more than half of the days can be considered "excellent" for urban tourism in lower altitude areas (Fig. 3). As expected, DJF months, however, do not seem to be optimal for outdoor tourist activities, showing a decrease with altitude on "excellent" days for urban tourism (Fig. 3). As five of the islands (western) exceed 1400 m in height, reaching 3718 m in Tenerife, it is clear that orography has a large impact on the surface climate distribution.

During the summer and shoulder months, the results show a robust and statistically significant improvement for the future periods in the highest areas, located in the central part of the western islands (Figs. 2 and 3). As evidenced in previous works (Expósito et al. 2015), the temperature increase is expected to be greater at higher elevations, that is, where the current cold temperatures are less suitable for certain activities. Therefore, these areas will benefit from expected future changes, with a higher percentage of "excellent" days for outdoor activities. On the other hand, the areas located in the south of Tenerife and Gran Canaria, and a large part of Fuerteventura and Lanzarote, will have fewer "excellent" days per year for tourism. These changes will be analyzed in more detail below, depending on the type of activity.

The HCIB expected changes are shown in Fig. 2. Although there are some tourist accommodations designed for rural or urban tourism that provide access to swimming pools and solariums, the vast majority of tourist infrastructures dedicated to "sun and beach" tourism are located in coastal areas, which is why the analysis will be focused on these zones. During winter and spring, the increase in the number of days considered "excellent" is noticeable in all coastal areas, which reinforces the idea discussed above of possible growth in tourism demand during these seasons. During the summer, there is a decrease in the number of "ideal" days in the south of Tenerife, Gran Canaria, and Fuerteventura. These areas concentrate most of the tourist accommodation in the Canary Islands. The behavior is similar in autumn, but the changes are much smaller, or almost zero. On average, the highest percentage of increase is expected in winter (DJF), at the end of the century, in the RCP8.5 scenario, where "excellent" days per month would increase by 148%, going from 5 days in the recent past to 14. On the other hand, in summer (JJA) a slight worsening

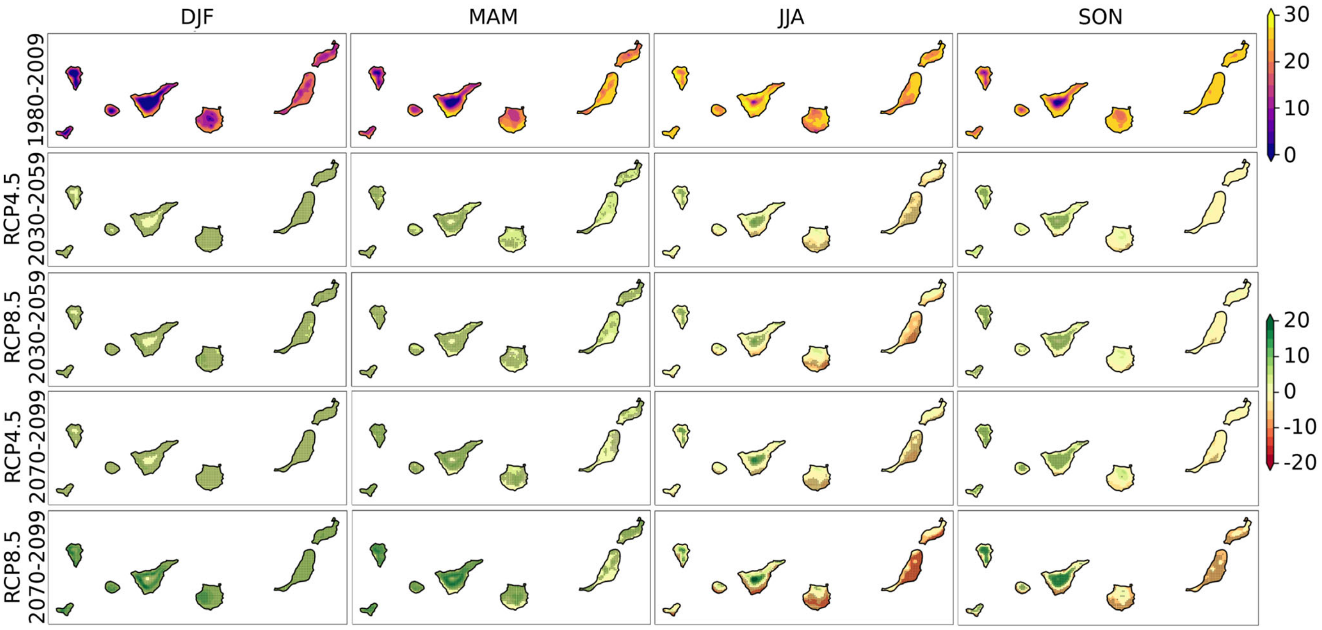

Fig. 3 Same as Fig. 2 but for HCIU80 (days per month)

of 0.6% is projected, at the end of the century, in the same scenario. In summer, the expected improvements in height are offset by the worsening in Fuerteventura, Lanzarote, and the south of Gran Canaria.

The TCI and HCIU indices are more general, in the sense that they are conceived for activities where the thermal sensation should be pleasant and with little rainfall, such as cultural visits and walks. Considering the recent past, during the summer, the number of days per month with "ideal" or "excellent" conditions is greater than 20 in almost the entire territory (Fig. 3). In many areas, HCIUB80 is close to 30 days, i.e., the whole month. During autumn, the areas with the most days considered "ideal" also occupy almost the entire territory, excluding the highest areas. Nevertheless, these higher areas may still be suitable for rural and mountain tourism. During spring, the situation is very similar, but the areas where most of the days are "excellent" for tourism are reduced and restricted to low altitudes or near the coast. In winter, these areas are even fewer.

Considering the expected changes for the future, a significant increase in the number of days with "excellent" conditions can be observed over most of the land in winter and spring. Although the Canary Islands are a tourist destination with little seasonality and a regular influx of tourists throughout the year, this fact could further increase the arrival of tourists in these seasons. Alternatively, during the summer and autumn, the projected increase in the number of days with "excellent" conditions is only observed in the currently cooler areas, that is, the highest parts of the islands. In these areas, the number of "excellent" days increases from about 10–15 per month during the current summers to almost the whole month by the end of the century (Fig. 3). The increase in the number of "excellent" days in these high altitude areas during the rest of the seasons is also considerable, going from a few days to more than half of the days per month, but with non-statistically significant changes. Elsewhere, the situation worsens, especially in summer, with a reduced amount of "ideal" days for this type of tourism. As might be expected, all these changes are most noticeable at the end of the century and in the worst-case scenario (RCP8.5).

Regarding the statistical significance of the results obtained, the percentage of gridpoints that meet the robustness criteria: p-value < 0.10 in at least two of the models and deviations in the same direction for the simulations driven by the three input models has been calculated. From the total of land pixels, the rate of gridpoints that meet the statistical significance criteria ranges from 10% for the autumn period in the mid-century RCP4.5 scenario (HCIU80 index), to 99% at the end of the century RCP8.5 scenario in winter (HCIU80 index) and spring (HCIB80 index). Gridpoints with robust changes are hatched (Figs. 2 and 3).

Changes in the monthly potential for tourist areas

The most visited islands are Tenerife and Gran Canaria, concentrating around 67% of all tourists. The areas where they mainly stay are in Los Cristianos (Tenerife) and Maspalomas (Gran Canaria), or in the surrounding areas because they have the highest annual hours of sunshine and the lowest rainfall (López Díez et al. 2019). Another two important beach destinations are Puerto de la Cruz

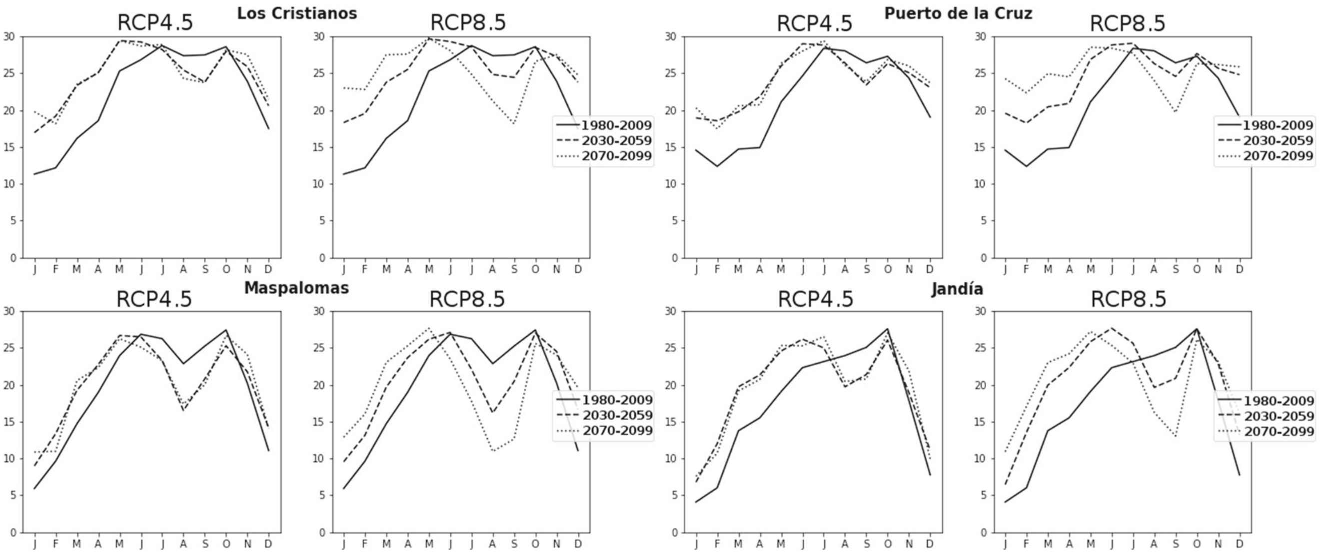

Fig. 4 Simulation of average monthly "excellent" and "ideal" days (HCIB80) for four beach tourism locations in the recent past and at mid- and end-century, for both emission scenarios (RCP4.5 and RCP8.5)

(Tenerife), where tourism development began in the Canary Islands, and Jandía (Fuerteventura), with an interesting dune system. These four zones have been selected for the analysis of the future change of beach tourism climatic conditions (see map in Fig. 1).

Four additional areas have been selected to analyze the impact of climate change on urban tourism. The first two being the provincial capitals, Santa Cruz de Tenerife and Las Palmas de Gran Canaria, which are the main cities and major port and cruise destinations in the islands. The other two areas are La Laguna (Tenerife) which was recognized as a World Heritage Site by Unesco and, finally, Santa Cruz de La Palma, which has a rich historical-cultural heritage.

In the above-mentioned areas, the mean monthly HCIB80 and HCIU80 days were compared, respectively, for the recent past and future projections (Figs. 4 and 5). The plotted indices correspond to the mean of the three simulations driven by the different GCMs. In this case, only the HCI indices have been used, not the TCI, since, as Scott et al. (2016) shows, the limitations of the latter index lead to an overestimation of the consequences of possible future climate changes.

Climate models predict an improvement in winter conditions for tourism in Maspalomas. For example, an increase in 8.5 "excellent" or "ideal" days for beach holidays in December. Conditions will also be more favorable in all other seasons, except summer. Climate change will result in a significant reduction of optimal days in summer months, for example, up to 13 fewer "excellent" days in August than in the recent past. The projections are very similar for Jandía, with a drastic reduction of "ideal" days during the summer. In the other two selected tourist areas the behavior is the same, but less severe.

Regarding the urban tourism, Las Palmas is the city with the largest simulated variations. In the worst scenario, at the end of the century, a reduction of 14 optimal days for tourism is expected in September. On the contrary, the projected improvement in March is 7 days. La Laguna shows a particularly low level of tourist comfort during winter, currently, only 6 days in February. These conditions are expected to improve by the end of the century. In the business-as-usual scenario, climate change will have a positive effect of 8 days.

In general, in all analyzed zones, the projected changes, for both beach and urban conditions, will evolve from a monthly behavior with a peak in the summer months to a situation with two peaks, corresponding to the best conditions for tourism, before and after the summer. "Excellent" and "ideal" days will be increased during winter and shoulder seasons, but in summer, the number of days with optimal leisure activity conditions will be substantially reduced. This change in the annual distribution has also been predicted in the Mediterranean area (Amelung et al. 2007; Amengual et al. 2014; Scott et al. 2016).

Sensitivity analysis of the future changes in tourism climatic conditions

To analyze which physical parameters are the largest contributors to the future improvement or worsening of the optimal days for tourism, the weights of each of the factors (Eqs. 2 and 3), to the total change, are represented

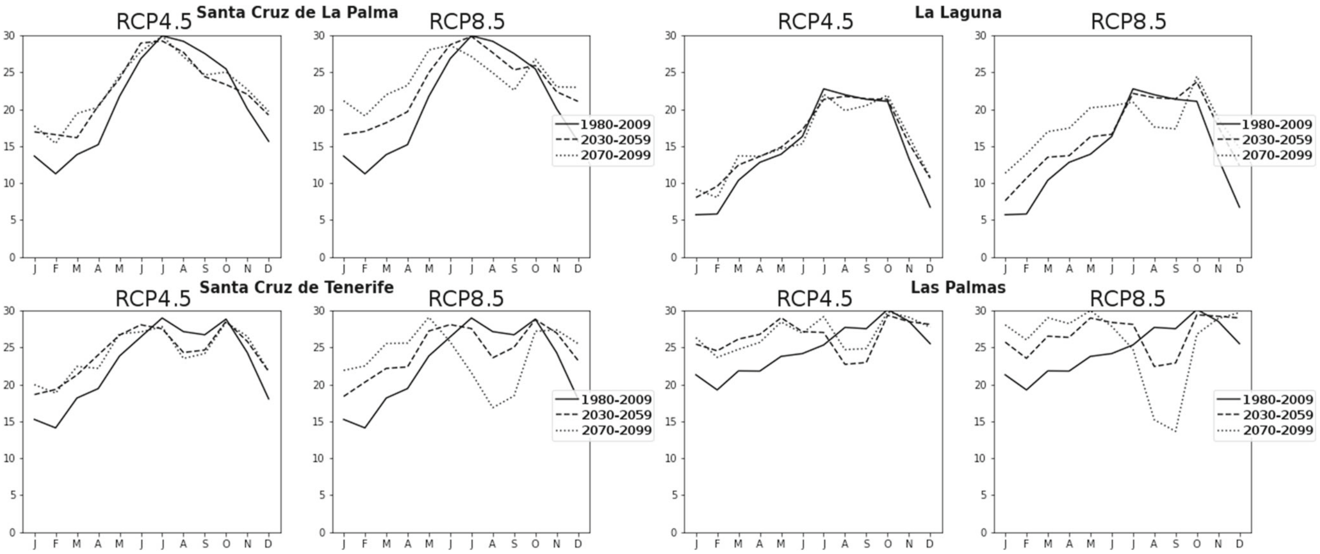

Fig. 5 Simulation of average monthly "excellent" and "ideal" days (HCIU80) for four city tourism locations in the recent past and at mid- and end-century, for both emission scenarios (RCP4.5 and RCP8.5)

in Fig. 6 for two characteristic locations. Due to the linear relationship between the different factors and the indices, the effect of each factor on the total change was calculated using finite differences.

A representative beach location, Maspalomas, and a city location, La Laguna, have been selected to illustrate the monthly impact of the HCIB and HCIU sub-indices, respectively. The comparison was made with the change in the future foreseen in the period 2070–2099, with the RCP8.5 scenario. Although the given weight to the thermal comfort in the computation of HCIB index is only 20%, in Maspalomas, except for October, the contribution of this sub-index to the future absolute variation, is greater than 75%, and up to 92% in April. Similarly, for the urban destination, La Laguna, the contribution of thermal comfort on the projected HCIU score change exceeds 62% every month, reaching 87% in September.

The importance of thermal comfort in the projected future changes can explain the values obtained for the HCIU80 index in the summer months in the southern areas of the islands (lower scores than in recent past), since for this index, temperature and relative humidity have a higher weight than for the HCIB80 (Fig. 3).

Discussion and conclusions

The Canary Islands are a unique laboratory to analyze the impact of climate change on tourism; the complex orography of most of the islands causes the impacts of global warming to be uneven throughout the territory.

In this paper, a climatic analysis of the future conditions for tourism, at the middle and end of the century has been carried out, using two emission scenarios, RCP4.5 and 8.5. However, the conclusions must be completed with the analysis of the issuing countries and other political or socio-economic parameters that are outside the scope of this study. For example, the climatic conditions for tourism in the UK and Germany, two of the most important source countries for the Canary Islands, are expected to improve in the future, especially during the summer (Amelung et al. 2007; Perch-Nielsen et al. 2010; Grillakis et al. 2016). This may reduce, during these months, one of the main drivers for traveling, mainly for beach tourists, the desire to find optimal weather.

The main factor influencing the future variation in tourism weather conditions is thermal comfort (weighing between 62 and 92%) above the rest of the factors: cloud cover, precipitation or wind. Although the thermal comfort is not an direct measurement, as it depends on the origin of the tourists (Lin and Matzarakis 2008) and may vary over time (Perch-Nielsen et al. 2010), the results presented in this work were based using the currently most widely used indices. The climatic projections show a future improvement in the weather conditions for the tourism in winter and shoulder seasons and a deterioration in summer.

Although, as far as the authors know, there are no future projections of climatic conditions for the tourism under climate change scenarios in the studied region (Alonso-Pérez et al. 2021; Simancas Cruz et al. 2020), the future degradation of conditions during summer and the improvement during spring and autumn is in agreement with previous studies in other regions. For example, Perch-Nielsen et al. (2010) obtained a similar behavior for several European regions using the TCI index, being very remarkable in the Iberian Peninsula and in the Mediterranean. Amelung and Viner (2006) and Amengual et al. (2014) projected similar results for the Mediterranean area and Hein et al. (2009) for Spain. Amelung et al. (2007), in a global study, shows the worsening in the summer months for the Mediterranean area, increasing ideal conditions in northern Europe and Canada and the southernmost countries in the other hemisphere. A more recent study (Demiroglu et al. 2020) uses the HCI indices, both urban and beach, to analyze possible future changes in Europe, also showing a significant deterioration of conditions during the summer in the Mediterranean

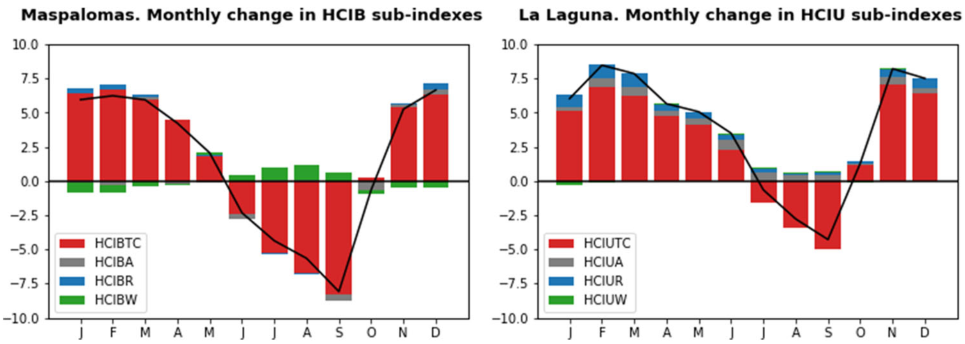

Fig. 6 Projected changes at the end of the century (RCP8.5 emission scenario) in a beach location (Maspalomas) and in a city (La Laguna) of the monthly values of the corresponding tourism indices, HCIB and HCIU, respectively. The contribution of each of the factors is also identified: Thermal comfort (TC), cloud cover or aesthetic (A), precipitation (R) and wind (W)

area and an improvement in the shoulder seasons. This future seasonal behavior has also been projected for some Mediterranean islands (Lemesios et al. 2016; Nastos and Matzarakis 2019), although based on other methodologies. However, projections for a Caribbean sun and beach destination (Gómez-Martín et al. 2020) show an increase in favorable days in the high season and a decrease in the low season. That is, making the current seasonality even more pronounced.

Currently, in the coastal areas of the islands, the "excellent" and "ideal" days for tourism exceed 20 per month, reaching 30 in the summer months and the south areas, with a sharp decrease in height. The southeastern or southwestern parts of the islands, where most of the hotel infrastructure is currently located, will worsen their tourist conditions in summer and autumn. They will experience a decrease in the number of optimal days that will be accentuated at the end of the century and in the highest emissions scenario. It is an obvious statement that tourism destinations will need to adapt to climate change (Scott et al. 2012). Tourist arrivals to the Canary Islands do not show a great seasonality (Gil-Alana 2010; ISTAC 2021); hence, not relying exclusively on the summer months could be an advantage considering future changes.

The high exposure level of the tourism sector to climate change effects cannot be denied. Climate projections into the future are intended to assist in the design of adaptation measures. Climate change has numerous consequences: increase in temperature and extreme events, decrease in rainfall, rise in sea level, etc. In this study, carried out in the Canary Islands, it is noteworthy that the climatic conditions for tourism will improve in winter and intermediate seasons, above all in high altitudes, but will worsen in summer, mainly due to the deterioration of thermal comfort. The possible advantages of these changes and the correct communication to the source markets must be taken into account by tourism marketing analysts.

One of the main limitations of this study is the use of indices that are highly dependent on thermal comfort, such as the TCI index, which has been discouraged by other authors. Nevertheless, it was included in the analysis for allowing intercomparison with previous studies. In addition, given the high spatial resolution required to perform the climate projections for the islands and the corresponding computational cost, the obtained ensemble is composed of only three members, corresponding to each of the GCMs used as boundary conditions. Despite these limitations, the climate projections of tourism indices are a useful tool to anticipate the risks of climate change in this sector. Future lines should perform the same projections in a more segmented way, taking into account specific activities and the differences in tourists' real assessments on thermal comfort or in situ observations. Socio-economic studies based on the data presented will be necessary to elaborate adaptation measures to improve destination resilience.

The adaptation measures involve the elaboration of sectoral plans that require coordination and cooperation between different administrations with competencies in tourism (state, regional, and local) (Olcina Cantos and Vera-Rebollo 2016) and implication of the other stakeholders, including tourism-related businesses and communities (supply-side). The loss of thermal comfort that it entails should imply the commitment to the supply of destinations and tourist facilities with zero-emission energy sources, the need for improvements in the construction, such as thermal insulation and thermal mass (Radhi 2009), and urban design of the destinations, considering green zones with artificial water bodies, high albedo materials, shading elements, morphology that facilitates air circulation, etc. The increase in the temperature will result in additional costs of air conditioning. Medium-term strategies focusing on higher value-added destination and income elasticity could help to absorb these costs without reducing profitability. Despite the current low seasonality of the number of tourists arriving to the islands, the prolongation of the hot period with an extension into spring and autumn could imply, in the medium term, the modification of the tourist season (Cantos 2020).

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Abbreviations The following abbreviations are used in this manuscript: CIA, Daily Comfort Index; CID, Daytime Comfort Index; HCI, Holiday Climate Index; HCI80, days with a HCI value greater than 80; IPCC, Intergovernmental Panel on Climate Change; TCI, Tourism Climate Index; TCI80, days with a TCI value greater than 80; UNWTO, United Nations World Tourism Organization.

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Declarations

Conflict of interest The authors declare no competing interests.

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