National Roadmap for Adaptation 2100
Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century

REPORT

WP2E – Climate Projections, Extremes, And Indices

Portugal Autonomous Regions

Final version

National Roadmap for Adaptation 2100

Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century

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Title: RNA2100 – Climate Projections, Extremes, And Indices - Portugal Autonomous Regions

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This report is a product of the National Roadmap for Adaptation 2100 project.

Through the Agreement on the European Economic Area (EEA), Iceland, Liechtenstein and Norway are partners in the internal market with the Member States of the European Union.

In order to promote a continuous and balanced strengthening of economic and trade relations, the parties to the EEA Agreement have established a and trade relations, the parties to the EEA Agreement established a multi-annual Financial Mechanism, known as the EEA. known as EEA Grants.

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1. Introduction

Islands are broadly defined as an area of land smaller than a continent surrounded by a water body, such as ocean, sea, lake or river. When there are several islands in the same geographical area they are referred to as an archipelago. There are around two thousand islands in the oceans of the world Islands have been long identified as being most vulnerable to climate change and climate extremes. The most immediate threat to islands is most likely related to changes in sea levels, variations in local and regional wave patterns, prevailing winds, soil moisture budgets and rainfall regimes (IPCC, 2007, 2012).

Islands share many characteristics like their small size, proneness to natural disasters and extreme events, limited natural resources, relative isolation and the fact they are surrounded by large expanses of water. These and other characteristics make islands highly vulnerable in a world with a changing climate. Therefore, the study of measures to adapt or mitigate the vulnerable nature of islands should be a high priority area, even if islands are only responsible for less than 1% of the greenhouse released worldwide. Some islands already begun to use economic resources into adaption measures (Nurse and Moore, 2005).

To develop strategies to successfully fight climate change, and minimize the human impact, there is a need for accurate climate information. Global climate models (GCMs) are the most effective tool currently available to study aspects of the large-scale and global climate. Despite being capable of reproducing the general circulations patterns, GCMs have limited capability in reproducing the regional climate due to their limited horizontal spatial resolution (Leung et al. 2003; Gao et al., 2006; Somot et al., 2006). Since the current GCMs do not have sufficiently horizontal resolution to simulate islands, many of the current island systems climatic studies refer to nearby ocean surface points with very different thermodynamic properties of earth points (IPCC, 2007). The coarse resolution of these models prevents a detailed analysis at regional scales (Gutowski et al. 2020).

To overcome GCMs limitations, several downscaling techniques have been developed in recent decades (Fowler et al. 2007). Statistical downscaling generally involves two stages. The first stage involves determining statistical relationships between local variables and a large-scale predictor. In a second phase the previously determined statistical relationship is used to simulate a local characteristic. The statistical downscaling can be addressed using regression techniques (Hewitson and Crane, 1996; Von Storch et al., 1993), correlations with regional weather patterns (Denis et al., 2002) or stochastic weather generators (Wilks, 1992). These methods have little computational requirements when compared with dynamical techniques, which allows for their rapid application to various GCMs outputs. However, they do not represent physical process and assume that a given relationship remains valid in the future climate.

Furthermore, the development of a robust statistical method relies heavily in a large observational reliable dataset which may be difficult to find especially in island systems.

Dynamical regionalization is based on the use of regional circulation models (RCMs) with higher horizontal and vertical resolutions over the study region. These regional models are based on a physical equation and are regarded as the best method available to capture the complex atmospheric system (Price and Flanningan, 2000). Currently regional models have typical horizontal resolutions of less than 10km and around 100 meters in the vertical coordinate system. These types of models can reproduce local scale effects that cannot be reproduced by the global climatic models; however, these methods require a large computational capability that restricts the number of scenarios that can be simulated (Goodess, 2000). Regional climatic models are capable to reproduce physically consistent local conditions (Laprise, 2008; Leung et al., 2003; Wang et al., 2004) allowing the development of high-resolution climatology in different types of terrain.

The relative merits of different regionalization methods have been subject to discussion (Murphy, 1999; Gibelin and Déqué, 2003). There appears to be advantage in the use of regional or global models with resolution increased compared to statistical techniques, as these assume that the statistical relationships that occur in the present climatic conditions will remain unchanged in the future, which can be physically inconsistent.

The manuscript is organized as follows: first we start with a small description of our study regions, followed by a description of the datasets and analysis methodologies employed. The error assessment of out downscaling simulations is evaluated in section 4; in section 5 we discuss the results of the future climate signal and finally in section 6 the results on the future climate change of the climate extremes are presented.

2. Study Regions

2.1. Azores Archipelago

The Azores archipelago includes nine islands that are in the North Atlantic, between latitudes of 36.5ºN and 39.5ºN and the longitudes of 24.5ºW and 31.2ºW. All islands are of volcanic origin and are distributed by three groups, West (Flores and Corvo), Central (Terceira, Faial, Pico, São Jorge and Graciosa) and East (São Miguel and Santa Maria). Azores were discovered and settled in the beginning of the 15th century by the Portuguese. The largest island, São Miguel, has around 760 square kilometers and the smallest, Corvo, has 17 square kilometers. The Portuguese highest peak can be found in Pico Island at 2351 meters.

Azores climate is mild and strongly influenced by the ocean in terms of temperature (influence of the Gulf Stream) and its territory is frequently affected by depressive systems associated with frontal surfaces that cross the Atlantic, with a high degree of humidity. On a regional scale the climate is influenced by the orography of each island, as well as by the reciprocal influence between neighboring islands, such as the case of Pico, São Jorge and Faial. During most of the year (September to March), the Azores region is frequently crossed by the North Atlantic storm-track, the main path of rain-producing weather systems. During late Spring and Summer, the Azores climate is influenced by the Azores anticyclone.

2.2. Madeira Archipelago

The Madeira archipelago is composed by two main islands, Madeira (the largest one) and Porto Santo (Northeast of Madeira). Madeira is located at 32.5ºN of latitude and 17ºW of longitude. Like the Azores the islands are of volcanic origin, Madeira is characterized by highly rugged orography with high peaks (highest peak, Pico Ruivo, around 1862 meters) and deep ravines, on the other hand Porto Santo has a smoother orography.

The climate is strongly influenced by the Gulf and Canary Currents, giving the archipelago mild to warm temperatures year-round. The relief, as well as exposure to prevailing winds introduce many micro-climates into the island which, combined with the exotic vegetation, is an important attraction factor for the tourism industry. The climate is largely influenced by the Eastern branch of the Azores anticyclone, especially from Spring to Fall. During the Winter season, eastward moving Atlantic low-pressure systems bring precipitation to the island and slowly moving depressions can provoke extreme precipitation events.

3. Data and Methods

3.1. Dynamical Downscaling Design

For the dynamical downscaling, we use the Weather Research and Forecasting Model version 4.2 (Skamarock et al. 2008). The WRF model is a non-hydrostatic model, suitable for simulating a wide range of scales, from thousands of kilometers to a few meters, with many available options in what concerns the model core and most physical parameterizations, making it appropriate for numerical prediction, climate, and LES simulations.

Dynamical downscaling of GCM simulations requires significant computational resources and even if those are available it takes a considerable amount of time. Before we committed to run the model, some tests were carried out to minimize model errors and the amount of time required to perform the simulations. After those tests, we realized that to minimize the amount of time required to run the simulations, the Azores simulations should be split to three (one domain per island group) instead of one single high-resolution domain covering all the island groups. These tests also showed that the model physics that minimize the errors should follow those described in Miranda et. Al, 2020.

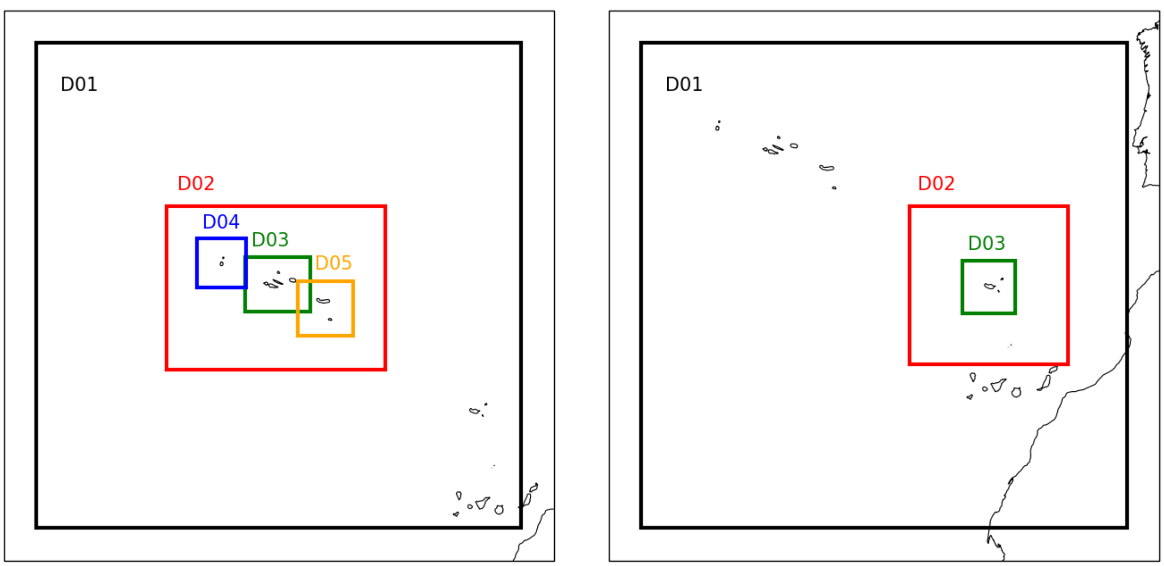

Figure 1 -The WRF model domains. Azores archipelago on the left and Madeira Archipelago on the right. Outer domain D1 at 27km horizontal resolution (black), D2 at 9km (red) and D3 at 3km resolution (green, blue and yellow).

For the present-day climate, four sets of simulations were performed, two for each archipelago. First a 42-year long simulation (1979 to 2020 – WRF_{e5}) was made for each archipelago. The simulations were forced by ERA5 reanalysis data (Hersbach, et al., 2020) every 3 hours, the setup has two nested domains using one-way nesting, the outer domain with 9km horizontal resolution (D2) and the inner domain with 3km horizontal resolution (D3/D4/D5). These simulations are used has a benchmark for the dynamical downscaling. To study climate change in both archipelagos, we run a second set of two historical simulations, these cover a 31-year period (1970 to 2000 – WRF_{ec}) that are forced every 6 hours with data provided by EC-Earth Veg GCM run in house for the 6^{th} Coupled Model Intercomparison Project Phase 6 – CMIP6 (Eyring et al., 2016). Unlike the ERA5 forced simulations, these use three nested domains due to constraints in the forcing data horizontal resolution, the outer domain has 27km horizontal resolution (D1) and the second and third domain match those used for the ERA5 simulations.

To study the climate change, two future periods were studied (2040 to 2070 and 2070 to 2100). For each period three different SPPs were considered, the best-case scenario (SSP126), the moderate emission scenario (SSP245) and a business-as-usual scenario (SSP585). All these six simulations were forced by the EC-Earth Veg GCM model data.

Table 1 - Summary of the simulations performed for each of the Archipelagos.

Acronym	Description	Resolution	Forcing	Period
WRF_{e5}	Historical Simulations (Synchronized)	9 km 3 km	ERA5	1979 to 2020
WRF_{ec}	Control Simulations (Non- Synchronized)	27 km 9 km 3 km	EC-Earth Veg (r6i1p1f1)	1970 to 2000
	Mid-21^{st} Century Climate Simulations SSP126 Mid-21^{st} Century Climate Simulations SSP245 Mid-21^{st} Century Climate Simulations SSP585			2040 to 2070
	End-Of-21^{st} Century Climate Simulations SSP126 End-Of-21^{st} Century Climate Simulations SSP245 End-Of-21^{st} Century Climate Simulations SSP585			2070 to 2100

3.2. Observational Dataset

This study uses surface observations of daily maximum and minimum air temperatures, recorded at 2 meters high, and daily precipitation. The meteorological observations datasets belong to the IPMA repository, and cover the period 1971 to 2000. For the Madeira Archipelago a total of twelve stations are available (one of which is at Porto Santo), and for the Azores a set of seventeen exists, two in the Western Group, eight in the Eastern Group and the remaining seven for the Central Group.

3.3. Evaluation Metrics

The ability of the WRF model downscaling to reproduce the present-day climate, was assessed by comparing the simulations results against the observational dataset. Since the model grid point locations don't match the observational points, the comparison is performed against the nearest land grid point to the station location. Only the WRF 3km horizontal resolution domain was considered here, with the air temperatures are corrected by an adiabatic adjustment of -6.5K/km to account for differences between the model height and the target height of the observations. We also compare the WRF downscaling results against both forcing datasets used. In these datasets the comparison is made against the closest grid point available regardless of its dynamical properties, and again we corrected the temperature to account for differences between model and target heights.

The present-day climate simulations forced with EC-Earth Veg have a daily non-synchronized climate (ERA5 simulations are synchronized), therefore only a statistical comparison can be performed between the WRF model downscaling and the observations. Since the different starting dates in both ERA5 and EC-Earth Veg forced simulations differ, the evaluation is only performed for the period 1980 to 2000 (1979 is discarded in the ERA5 simulation as model spin-up).

Here we consider five different error metrics, the metrics are described in the WP2 Climate Projections, Extremes and Indices Report for the Portugal Mainland.

3.4. Definition of Climate Extremes and Climate Indices

To describe the climate projections affecting the two Portuguese archipelagos, a description of the climate was constructed based on a set of climate indices (CIs). These indices were computed from hourly model output considering three different periods - historical (1971-2000), mid-21st-century (2041-2070) and end-of-21st-century (2071-2100). Additionally, three different emission scenarios were considered for each future period: SSP126, SSP245 and SSP585. The climate indices and the climate extremes used here, are described in full detail in WP2 Climate Projections, Extremes and Indices Report for the Portugal Mainland.

4. Downscaling Error Assessment

In climate change assessment studies, it is fundamental to evaluate the ability of the RCM historical simulations to represent the present-day climate. Therefore, an evaluation of the precipitation and maximum and minimum air temperature was performed for the WRF downscaling simulations and the respective forcing, by comparing the model result against the observational dataset supplied by IPMA. To simplify the comparison, all the statistics presented here are means taken from the individual results of the different stations available and were grouped into three groups in the Azores Archipelago (Western, Central and Eastern) and into a single group in the Madeira Archipelago.

4.1. Madeira Archipelago

4.1.1. Precipitation

The monthly statistics for the Madeira Archipelago are showed in Figure 2. The normalized BIAS shows a clear improvement of the dynamical downscaling runs over the global circulation models that forced them. All models underestimate the total precipitation in Madeira. The EC-Earth Veg shows a negative BIAS around 60% of the mean, the model forced by this GCM (WRF_{ec}) does a good job correcting the lack of precipitation but still predicts around 20% less precipitation occurring in the region. The ERA5 Reanalysis, like expected, is better representing the total precipitation in the region with a negative BIAS of around 32%, again the dynamical downscaling (WRF_{e5}) corrects these statistics with a bias around 5% of the mean.

Due to the unsynchronized nature of the simulations (WRFec and EC-Earth Veg) its correlations with observations are not relevant on short time scales, but will incorporate a signal from the annual cycle and decadal trends. This needs to be taken into account when interpreting correlation but also RMSE, MAE and MAPE. BIAS and NTSD are, however insensitive to time synchronization and can be directly compared between simulations.

The synchronized simulations WRF_{e5} and ERA5 have correlations above70% if we look at the daily data and near 95% in a month or seasonal scale. In general, the correlations of the dynamical models match those of the GCM forcing then, with marginally higher correlations. Looking at the local variability, we notice large gains in the downscaling models when compared with the forcing models, in all timescales the dynamical downscaling simulations have values between 0.7 in WRFec and above 0.8 in the WRF_{e5}. The reanalysis reaches values of around 0.5. The RMSE of reanalysis is around of 2.2mm/day on a daily scale and of about 1.9mm/day at the seasonal scale. The WRF_{e5} simulations have the smallest error with values between 1.5mm/day in a daily scale and 0.8mm/day in both monthly and seasonal scales.

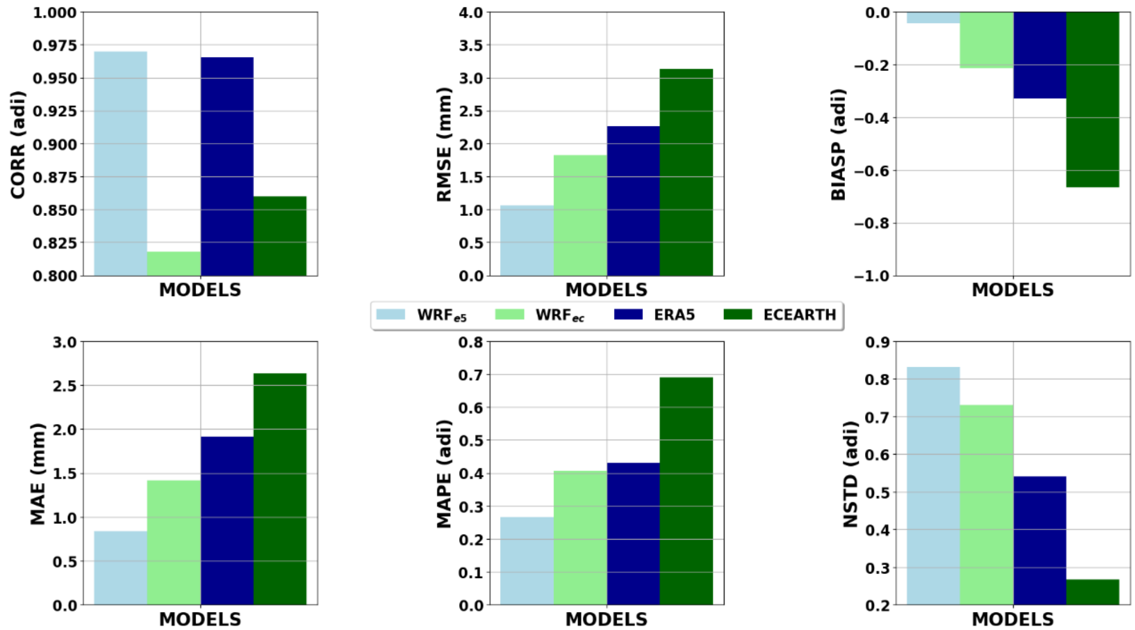

Figure 2 - Precipitation monthly statistics for the Madeira Archipelago. WRFe5 in light blue, WRFec in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and WRFe5 are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

4.1.2. Maximum Temperature Evaluation

Looking at the maximum air temperature statistics all four models underestimate the temperature in the Archipelago. The mean errors in the global models are high (figure 3), ranging from 4.8°C (EC-Earth) to 2.2°C (ERA5).

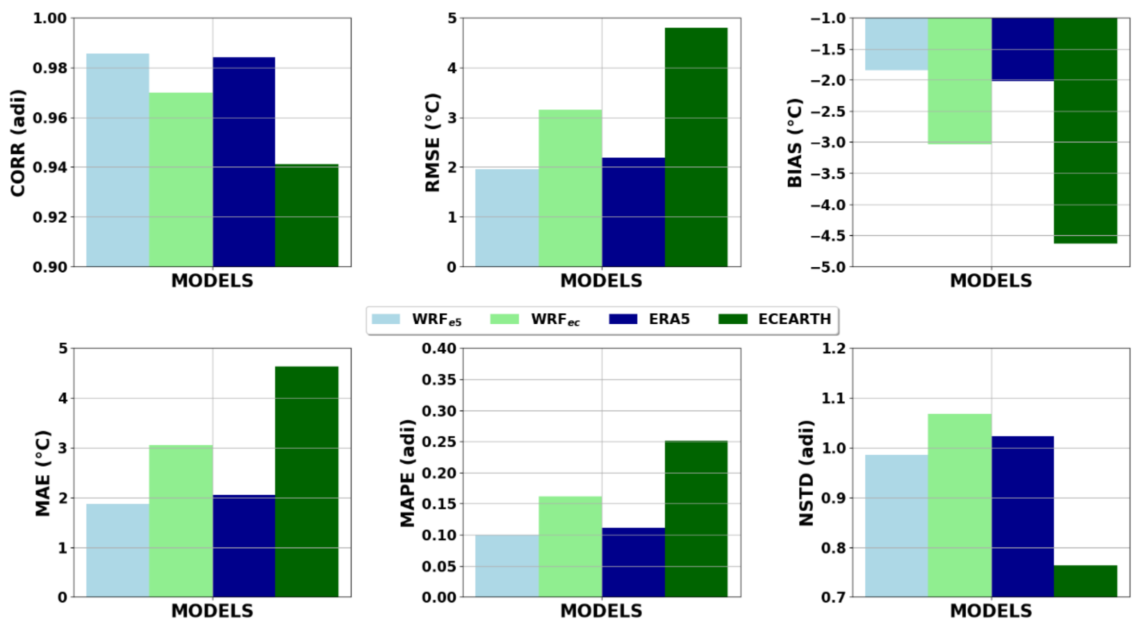

Figure 3 – Maximum air temperature monthly statistics for the Madeira Archipelago. WRFe5 in light blue, WRFec in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green.Note that only ERA5 and WRFe5 are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

The WRF_{e5} errors are smaller than those of the ERA5 forcing, with values around 2.0°C in all timescales. The WRF_{ec} despite improving in relation to the EC-Earth simulation still has means errors over 3°C in all timescales. All models have high correlations with values over 90% in all timescales and the regional models are slightly better than the global models. The local maximum air temperature is well explained by all four models, the EC-Earth model explains 0.7 of the local variability in all temporal scales and the remaining three models all have values of around 1 in all timescales.

4.1.3. Minimum Temperature Evaluation

The mean errors (Figure 4) in the minimum air temperature are smaller than those we found in the maximum air temperature. The WRF_{e5} errors are smaller than those in the ERA5 reanalysis with values of around 1.2°C in the daily data and below 1°C in the remaining timescales, ERA5 errors are above 1.5°C in all timescales. Unlike the maximum air temperature, the values in both these simulations are overestimations. The errors from the WRF_{ec} simulation are higher than the forcing data, the errors range from 1.7°C in the day scale and drop to 1.3°C at the seasonal scale, the EC-Earth are around 0.5°C smaller across the different temporal scales. It's noteworthy that the EC-Earth follows ERA5 and WRF_{e5}simulations and overestimates the maximum air temperature, but the WRF_{ec} is underestimating the temperature.

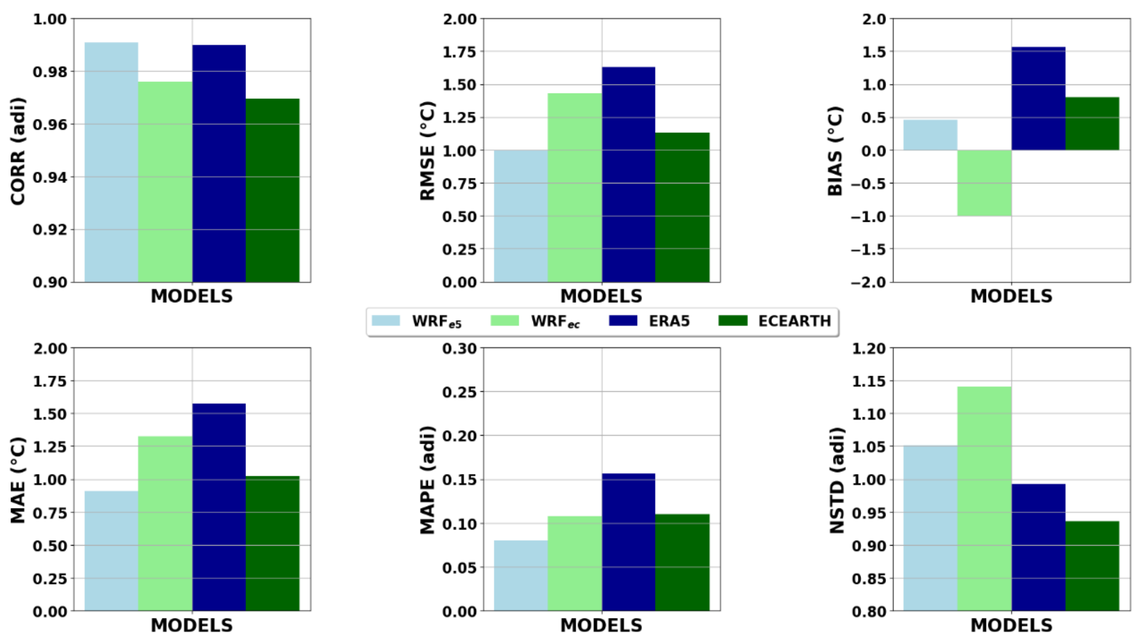

Figure 4 - Minimum air temperature monthly statistics for the Madeira Archipelago. WRFe5 in light blue, WRFec in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and

WRFe5 are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

Again, the correlations are above 90% in all temporal scales regardless of the model we look at. The local variability is well explained by all models (values varying between 0.9 and 1.1), with both global circulation models underestimating the local variability and both dynamical downscaling models overestimating the variability in the region.

4.2. Azores Archipelago

4.2.1. Precipitation Evaluation

4.2.1.1. Central Group

The monthly statistics for the Central Group of the Azores Archipelago is showed in figure 5. As we can see, both global models underestimate the precipitation of the region with values slightly above 20% for the EC-Earth model and close to 16% in the reanalysis. The downscaling models, on the other hand, overestimate the precipitation occurring in the Central Group of the region, with WRF_{ec} overestimating by close to 30% and the WRF_{e5} having 12% more precipitation in the region. Correlations in the daily range are low for the WRF_{ec} and EC-Earth simulations (near 30% in both simulations), but they rise to 80% in the monthly scale and are near 90% in a seasonal scale.

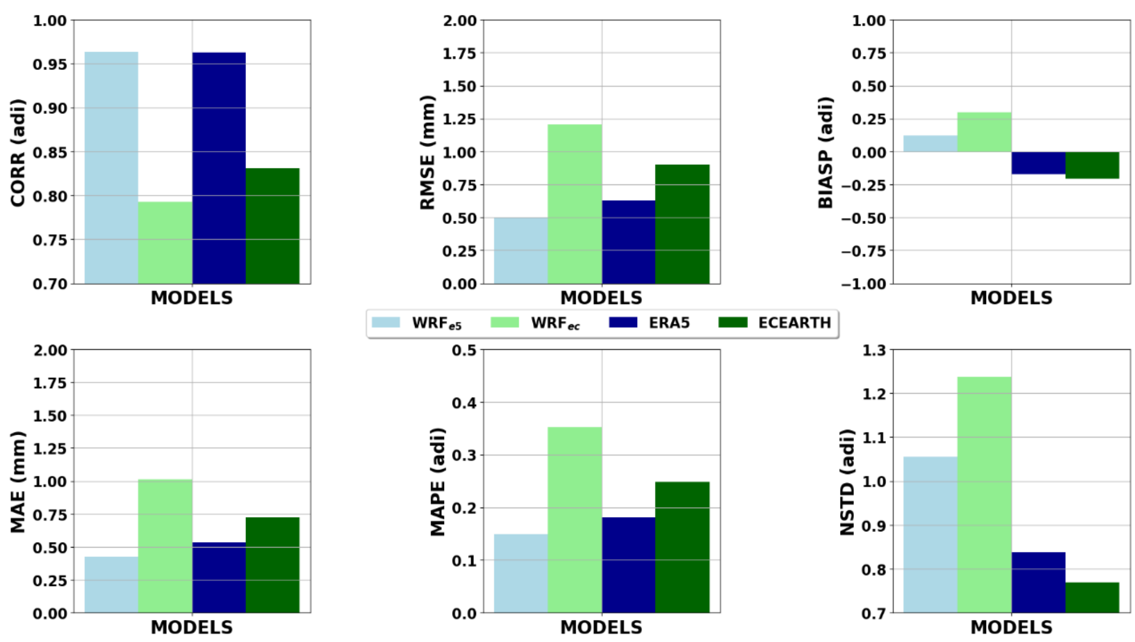

Figure 5 – Precipitation monthly statistics for the Central Group of the Azores Archipelago. WRF_{e5} in light blue, WRF_{ec} in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green.Note that only ERA5 and

WRF$_{e5}$ are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

The WRF$_{e5}$ and the ERA5 do much better at the daily scale, due to the synchronized nature of the runs, with values of around 70% in the daily scale rising to values above 90% in both monthly and seasonal scale. The normalized standard deviation shows that the downscaling models and both global models explain the variability quite well, with both downscaling models having NSTD values above but closer to 1, while both GCM values varying between 0.6 (EC-Earth in a daily scale) to 0.9 (ERA5 in a seasonal scale). The root mean square errors (RMSE) in a daily scale show that the global models have minor errors if we look at the daily data, at longer time scales the errors of all models drop (values near or below 1mm/day) and the WRF$_{e5}$ simulations errors are lower than ERA5, while the WRF$_{ec}$ errors are still a little bit higher than those of the EC-Earth simulation.

4.2.1.2. Eastern Group

In the Eastern Group of the Azores Archipelago, the normalized bias (figure 6), again shows that both global models underestimate the total precipitation occurring in the region.With the EC-Earth showing a lack of around 45% of precipitation and the reanalysis predicting 32% less precipitation. The WRF$_{e5}$ again can predict the total amount of precipitation quite well (underestimates by4%) and the WRF$_{ec}$ having 18% more precipitation occurring in the region. Like for the Central group, the daily correlations of the WRF$_{ec}$ and EC-Earth combo are low (below 30%), but they do rise to values near or above 90% in a monthly and seasonal scale. Again, the correlations of the WRF$_{e5}$ and ERA5 are better in all timescales, with near 70% in a daily scale rising to values near the 95% at a monthly or seasonal time frame. Looking at the normalized standard deviation, both downscaling models do a better job explaining the local variability in the region, with values varying between 0.9 to 1.1 in all time frames.

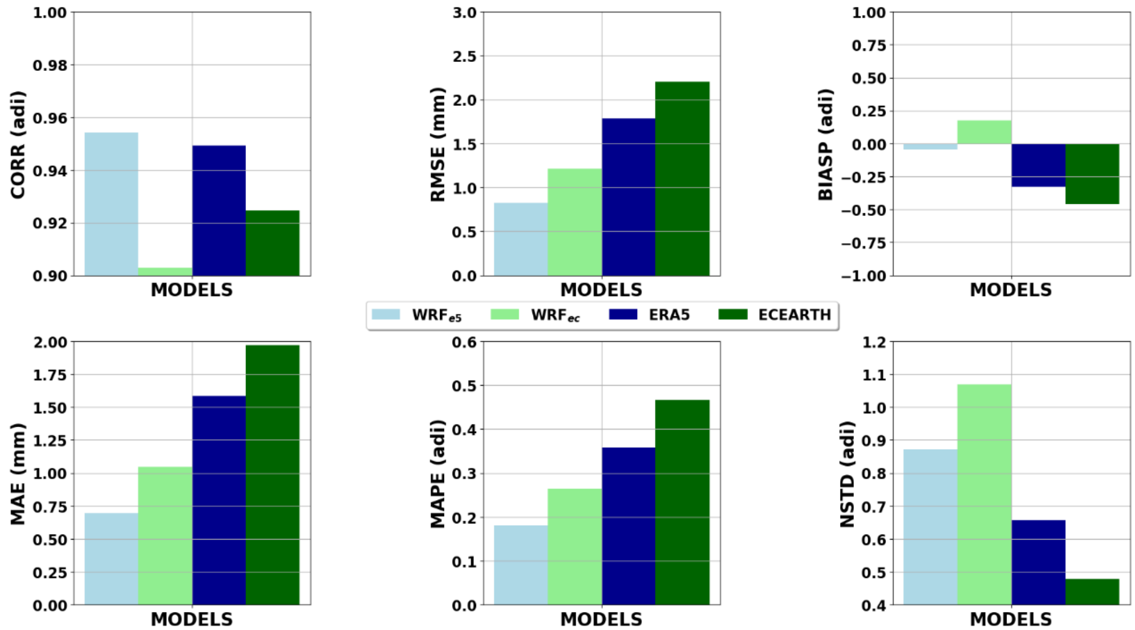

Figure 6 - Precipitation monthly statistics for the Eastern Group of the Azores Archipelago. WRF_{e5} in light blue, WRF_{ec} in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green.Note that only ERA5 and WRF_{e5} are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

The global models in all timescales can only explain 40% to 60% of the local variability. Looking at the daily data, the WRF_{ec} and EC-Earth have similar means errors (near 3mm/day), with WRF_{e5} (2.0mm/day) outperforming the ERA5 (2.5mm/day). In the longer timescales, both downscaling models clearly outperformed the global models with errors near or below 1mm/day, while the global models errors are above 1.6mm/day.

4.2.1.3. Western Group

In the Western Group of the Azores, the normalized bias in figure 7, again shows that both global circulation models underestimate the total precipitation occurring in the region by about 20%. The WRF_{e5} shows once more the better result with an underestimation of near 7%. The WRF_{ec} model results in the region are not great, overestimating the total precipitation occurring in the region by almost 50%. All models in the region have lower correlations in comparison with the other groups in the Archipelago. Daily data shows correlations near 20% in both WRF_{ec} and EC-Earth rising to 70% in a monthly scale and near 90% at the seasonal scale. In WRF_{e5} correlations are, of course, higher at a daily scale (near 70%), rising to values of 90 % in both monthly and seasonal timescales.

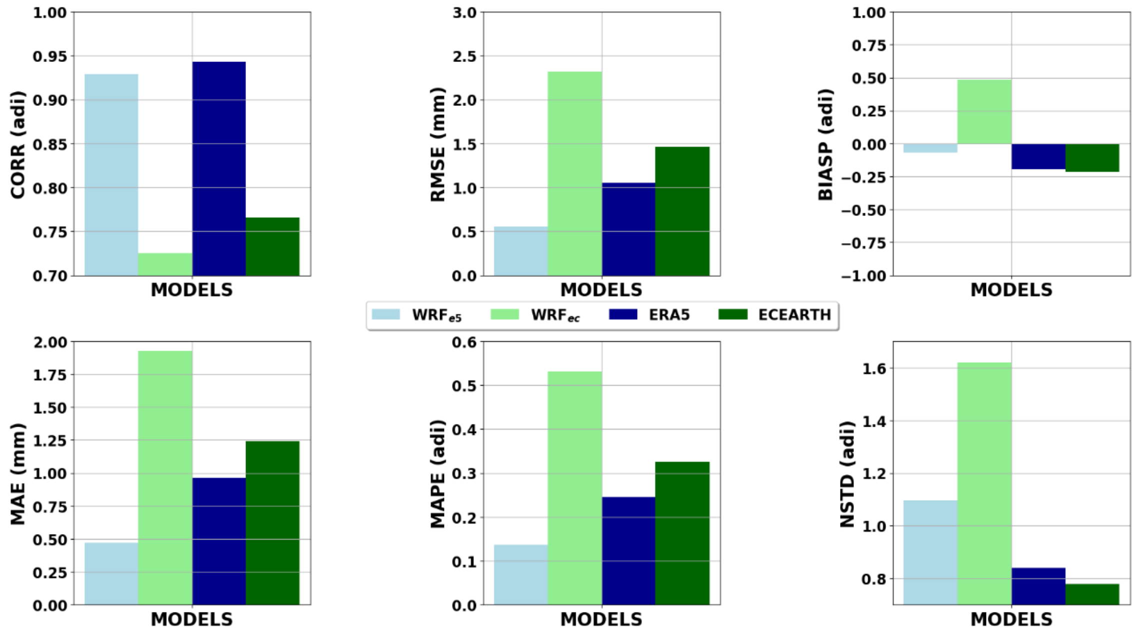

Figure 7 - Precipitation monthly statistics for the Western Group of the Azores Archipelago. WRF_{e5} in light blue, WRF_{ec} in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and WRF_{e5} are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

The normalized standard deviation shows that the WRF_{e5} simulation does a very good job explaining the local variability with values close to 1 (overestimating) in all timescales. The second downscaling simulation, WRF_{ec}, overestimates the local variability with values that reach 1.6 in a monthly timescale. Both global models have similar results in the region, with the models explaining only 60% of the local variability in a daily scale, in the longer timescales the values rise to around 80%. Looking at daily data, we observe large mean errors in WRF_{ec} and EC-Earth simulations (near or above 4mm/day), the error drop to below 2mm/day in a seasonal timescale but in all the temporal scales the WRF_{ec} shows bigger errors when compared to EC-Earth. The WRF_{e5} and ERA5 simulations at a daily level have similar results (errors around 2.5mm/day), but in the longer timescales the WRF_{e5} statistics are better than those of the ERA5, with ERA5 errors close to 1mm/day and the WRF_{e5} near 0.5mm/day.

4.2.2. Maximum Temperature Evaluation

4.2.2.1. Central Group

The monthly statistics for the Central Group of the Azores Archipelago is presented in figure 8. Results show that both WRF_{ec} and EC-Earth have high errors in all timescales with values near 3.5°C, errors in the reanalysis are around 2.5°C and the WRF_{e5} does a better job with errors dropping below 2°C. In all model simulations the local maximum air temperature is underestimated. All timescales show good correlations with observations, with values above 90% in all timescales and the downscaling models have the slightly better correlations than the global models.

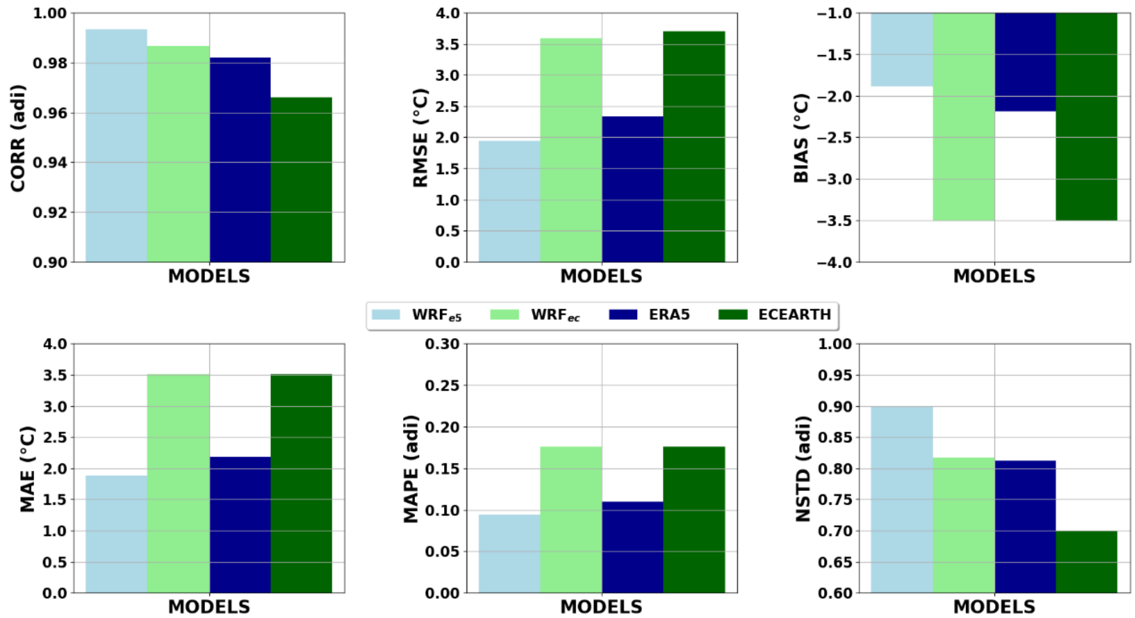

Figure 8 - Maximum air temperature monthly statistics for the Central Group of the Azores Archipelago. WRF$_{e5}$ in light blue, WRF$_{ec}$ in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and WRF$_{e5}$ are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

Looking at local variability, we see that the WRF$_{e5}$ and WRF$_{ec}$ models explain better the local variability (values of 0.8 in WRF$_{ec}$ and 0.9 in WRF$_{e5}$). The global models have lower NSTD with EC-Earth having the lower result with values close to 0.7 in all timescales.

4.2.2.2. Eastern Group

In the Eastern Group of the Azores Archipelago, the root mean square errors (figure 9) shows that the global models have slightly lower errors, again the WRF$_{ec}$ and EC-Earth have higher errors with values close to 3.6°C in both cases, the WRF$_{e5}$ and ERA5 simulations do better and have errors around 1.5-1.7°C in all timescales. Like the results for the Central Group of the Azores Archipelago, the maximum air temperature is underestimated in all models. Correlations are high in all timescales and models, with values near or above 95%. All models do a fair job explaining the local variability, with the reanalysis having values close to 90%, EC-Earth values are around 80% and both downscaling models scoring between those two values with WRF$_{e5}$ having slightly better scores than WRF$_{ec}$.

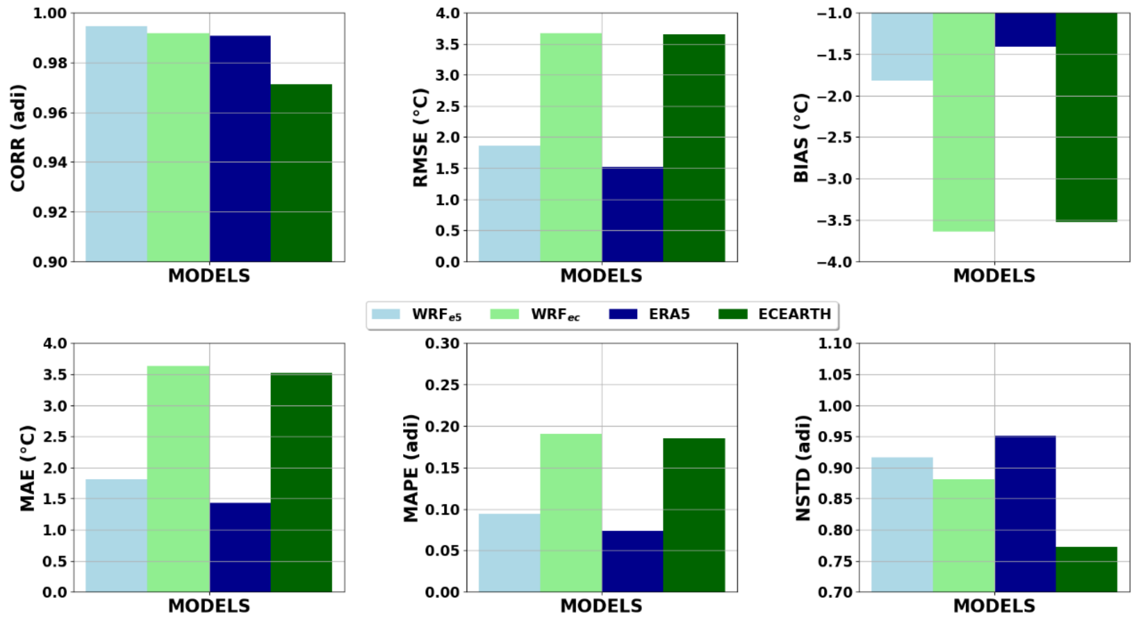

Figure 9 - Maximum air temperature monthly statistics for the Eastern Group of the Azores Archipelago. WRF_{e5} in light blue, WRF_{ec} in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and WRF_{e5} are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

4.2.2.3. Western Group

In the Western Group of the Azores Archipelago, again we see that all models underestimate the local maximum air temperature. The means errors (figure 10) show that both WRF_{ec} and EC-Earth have similar results with errors near 3.8°C, the reanalysis errors are around 2°C and the WRF_{e5} simulation has the smallest errors with values around 1.8°C in all timescales. Correlations in all temporal scales are extremely high with values near or above 95% for all models, with the downscaling models having the higher correlations. The local maximum air temperature variability is well explained in all the models and timescales (ranging from 0.75 to 0.9), and once again, the downscaling models have better statistics than the global models.

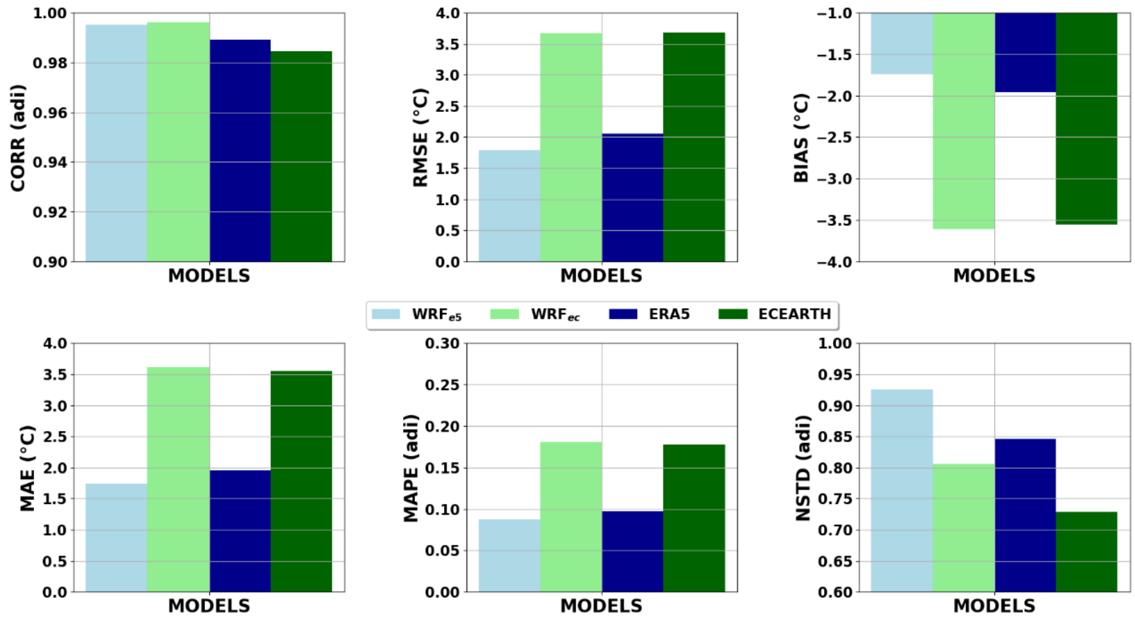

Figure 10 - Maximum air temperature monthly statistics for the Western Group of the Azores Archipelago. WRFe5 in light blue, WRFec in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and WRF_{e5} are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

4.2.3. Minimum Temperature Evaluation

4.2.3.1. Central Group

The monthly statistics of the minimum air temperature in the Central Group of the Azores Archipelago is presented in figure 11. The statistics reveal that the WRF_{ec} clearly underestimates the minimum air temperature in the region with errors near 1.9°C, the EC-Earth model that forces that downscaling simulation error is below 1°C in all timescales (overestimating). The reanalysis data errors are also high, overestimating the local minimum air temperature by around 1.8°C in all timescales. The WRF_{e5} errors are near or below 1.2°C in all timescales underestimating the local minimum air temperature. The correlations between models and observations are high, with values above 90% in the daily scale rising to values above 95% in the remaining timescales. The local variability is well explained by all the models (all values near or above 0.9), with the downscaling models having better scores when compared with the global models.

4.2.3.2. Eastern Group

In the Eastern Group of the Azores Archipelago the minimum air temperature is underestimated by the WRF_{ec} simulations while the remaining models overestimate the local minimum air temperature. The mean errors (figure 12), shows that the reanalysis errors are above 2°C in all timescales, the WRF_{e5} errors are below 0.9°C.

Again, the EC-Earth model errors are below the ones we find in the WRF_{ec} simulation, EC-Earth errors are below 1.3°C while the downscaling model errors are closer to 1.5°C. Correlations in the region are high with all models and timescales having values above 95%. Looking at the model NSTD, we find that all models do a great job explaining the local variability of the minimum air temperature, with all values varying between 0.9 and 1.1.

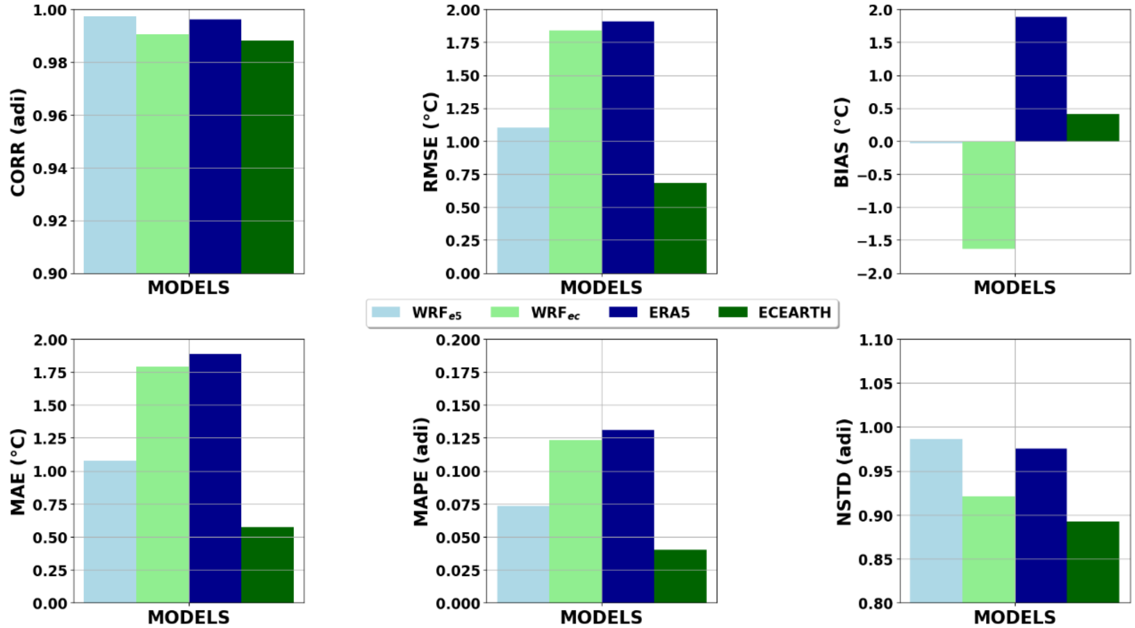

Figure 11 - Minimum air temperature monthly statistics for the Central Group of the Azores Archipelago. WRF_{e5} in light blue, WRF_{ec} in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and WRF_{e5} are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

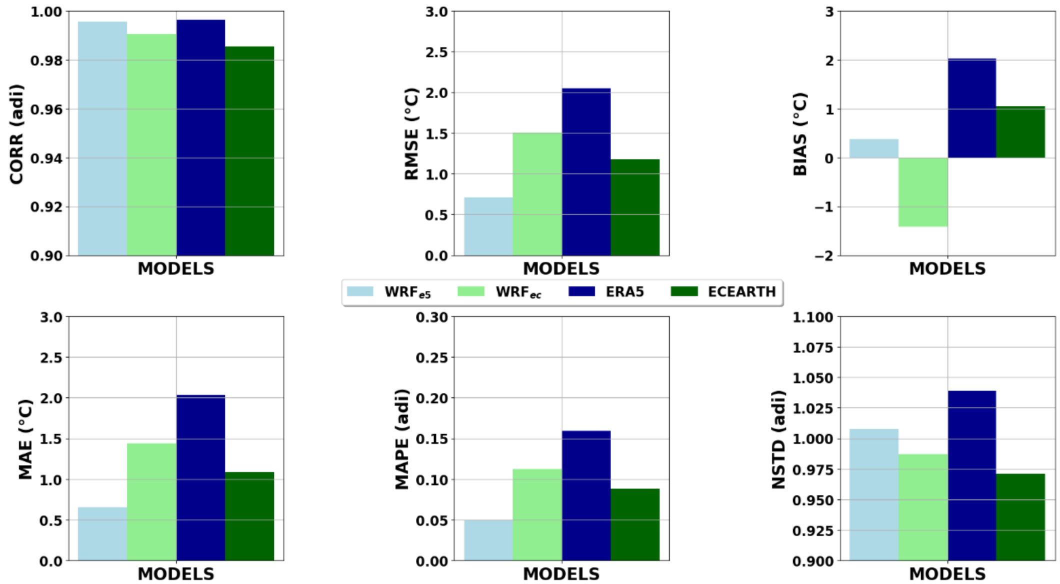

Figure 12 - Minimum air temperature monthly statistics for the Eastern Group of the Azores Archipelago. WRF_{e5} in light blue, WRF_{ec} in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and WRF_{e5} are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

4.2.3.3. Western Group

In the Western Group of the Azores Archipelago, the WRF_{ec} and EC-Earth models underestimate the local minimum air temperature, while the remaining models overestimate. Again, the WRF_{e5} simulation as the lowest errors (figure 13) with values below 0.9°C, the ERA5 data used to force that simulation errors are above 1.5°C.

The EC-Earth model outperforms the reanalysis with errors ranging from 1.2°C in a daily scale to below 0.7°C in a seasonal time frame. The errors in the WRF_{ec} simulations are close to 2°C at the daily scale and drop near 1.6°C at the seasonal level. Correlations between observations and models in the region are high with values ranging from 90% (daily) to 98% (seasonal). The local minimum air temperature is well explained, by the WRF_{e5} and ERA5 with values near 1 in both monthly and seasonal timescales, the set WRF_{ec} and EC-Earth stats are lower however both models values are above 0.9 in all timescales.

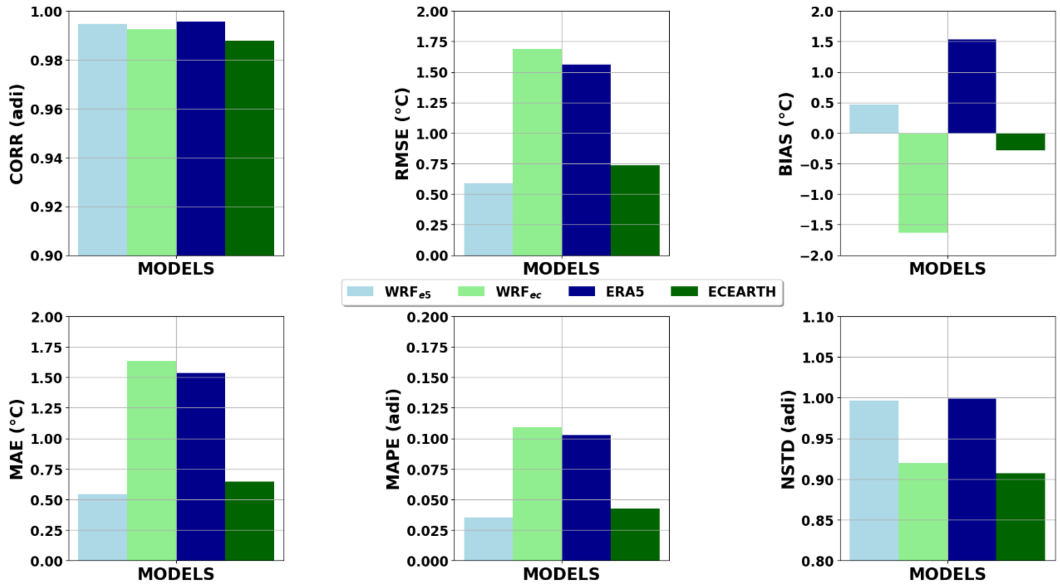

Figure 13 - Minimum air temperature monthly statistics for the Western Group of the Azores Archipelago. WRF$_{e5}$ in light blue, WRF$_{ec}$ in light green, ERA5 Reanalysis in dark blue and the EC-Earth Veg in Dark green. Note that only ERA5 and WRF$_{e5}$ are synchronized, the statistics concerning the unsynchronized simulations result from the annual cycle and decadal trends.

5. Annual and Seasonal Downscaling Mean Changes

5.1. Madeira Archipelago

5.1.1. Temperature

The RCM simulations project an increase of annual averaged daily mean air temperature in both Madeira Archipelago Islands (figure 14). Comparing against the 1971-2000 reference period the warming predicted for the end-of-the century period can reach 5°C in the SSP585 scenario in Madeira and around 4.5°C for Porto Santo.

For the best-case scenario (SSP126) for the end-of-the century projections show an increase of 2.5°C for both islands, these values increase to 3.5°C in the moderate emission scenario (SSP245). For the mid-century runs the warming in both islands are nearly equal and varies between 2.2°C in the SSP126 scenario and around 3°C for the SSP585 projection.

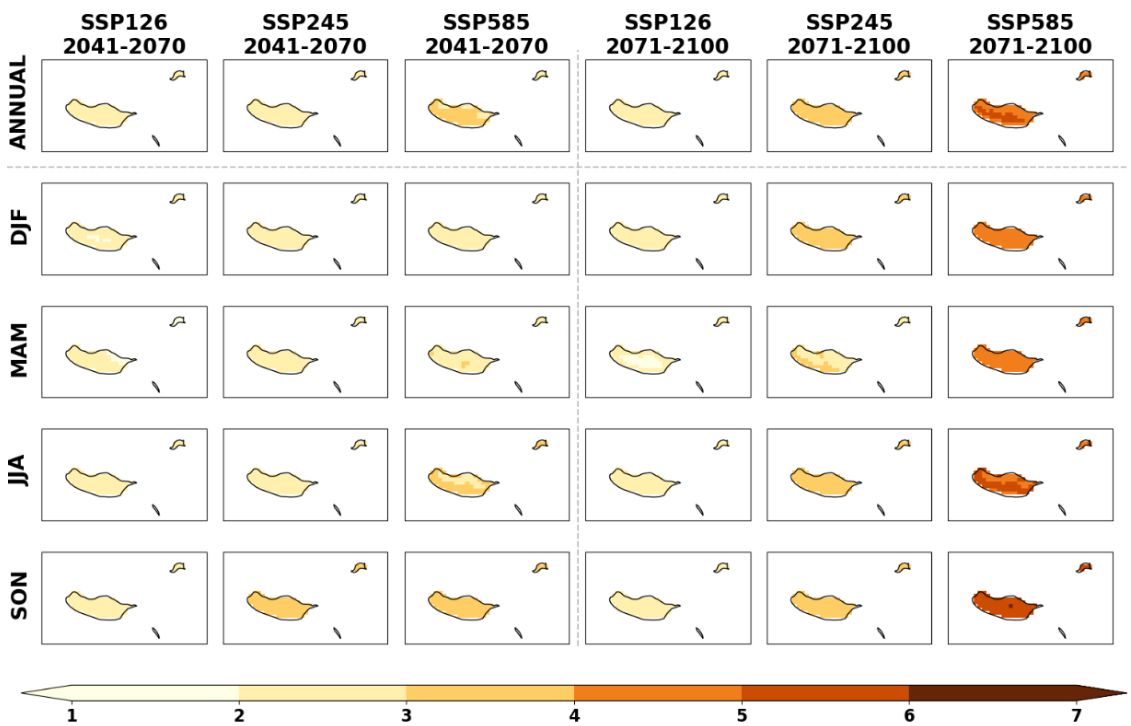

Figure 14 - Future projected changes in daily mean air temperature for Madeira and Porto Santo Islands (Units: °C).

The air temperature shows relevant seasonality, its increase tends to be higher in the summer and autumn seasons and lower in the winter and spring months. In the mid-century projections the islands warming tends to be homogenous throughout both islands and by the end of the century the increase of air temperature is higher in Madeira Island interior comparing with the coastal zones. Looking at maximum and minimum air temperature, it shows similar patterns and warming trends comparing against the mean daily air temperature.

5.1.2. Precipitation

The total annual precipitation projections are shown in figure 15. For the SSP126 scenarios both periods in study show an increase in annual precipitation, 2% for the mid-century and up to 12% for the end-of-the century projection. For the period 2071-2100 in the SSP126 scenario all seasons show increased precipitation, during the 2041-2070 period only in the spring months we see a decreased in precipitation. In the moderate emission scenario for the mid-century model predicts a gain of 5% in precipitation and a loss of 5% for 2071-2100.

For the SSP585 scenario precipitation anomalies show a decrease of only 2% in the mid-century and a 14% precipitation loss for the end-of-the century. In all the scenarios we see a strong seasonally variability. In spite of the annual precipitation anomalies the precipitation loss/gain is uniform throughout the islands. In the seasonal timescale we can see a north-south gradient in the anomalies in the SSP126 scenario. The remaining scenarios precipitation loss seems to be located along the coastal regions.

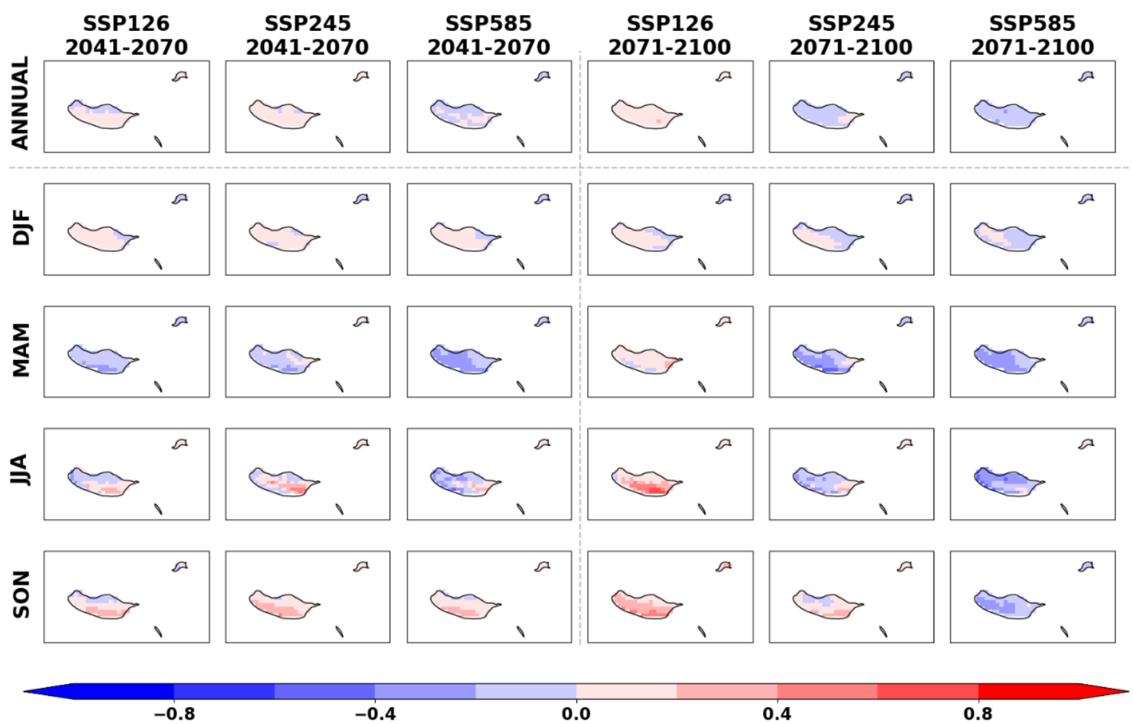

Figure 15 - Future projected changes in total precipitation for Madeira and Porto Santo Islands (Units: %/100).

5.1.3. Wind

The RCM simulations show a decrease between 1%-2% for all the scenarios for the mid-century period (figure 16). By the end-of-the century we see a decrease of values around 3% for all scenarios. Seasonally the variability is strong, with bigger losses in wind speed in the spring (5%-15%) and autumn (5%-10%).

During the mid-century, all scenarios show an increase of wind during winter, but by the end of the century all the scenarios report losses. During summer, almost all the RCM simulations show a minor increase of wind in the mountainous regions of Madeira Island and a decrease along the coast.

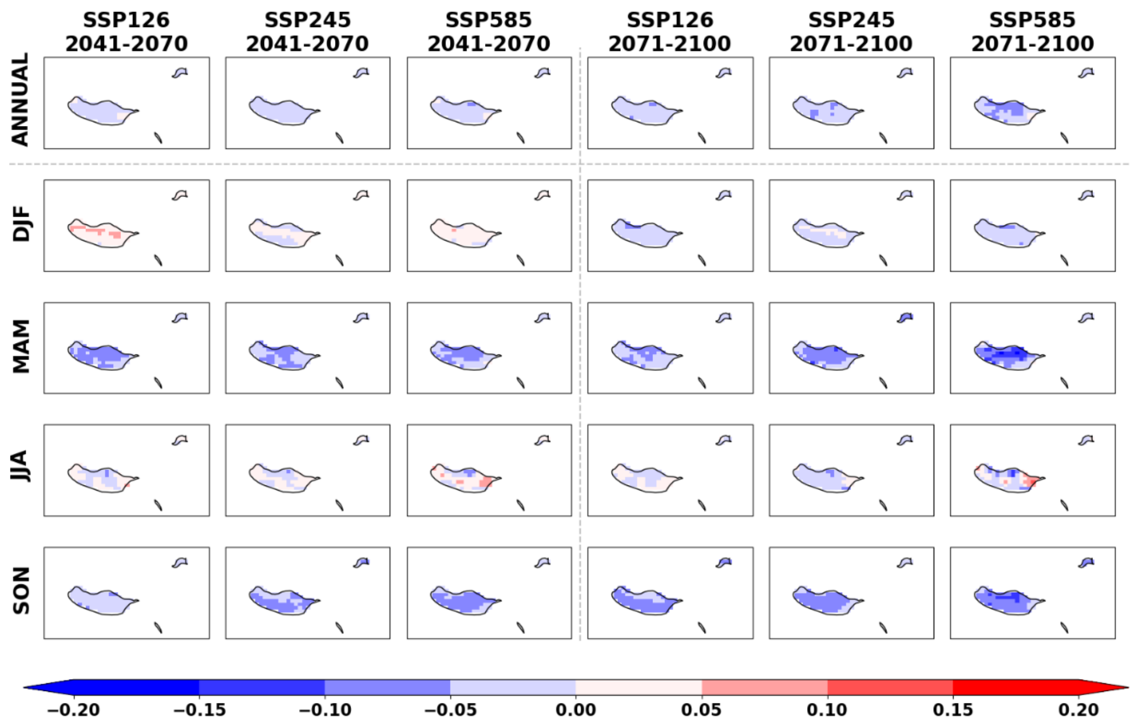

Figure 16 - Future projected changes in daily mean wind speed for Madeira and Porto Santo Islands (Units: %/100).

5.2. Azores Archipelago

5.2.1. Temperature

5.2.1.1. Central Group

The future projections show a warming anomaly in all Central Group Islands in the Azores Archipelago (figure 17). Due to proximity of the islands, it's not surprising that we can't find major differences in the warning trend in the different islands in the Central Group. Results show that by the end of the century all islands suffer from an increase in air temperature ranging from around 2.5°C in the best-case scenario and a larger increase of nearly 5.0°C in the worst-case scenario.

In the mid-century runs we observe an increase of temperature ranging from a maximum of around 3.3°C in the SSP585 scenario to an increase of around 2.3°C in the SSP126 scenario.

By the end of the century, we notice a high seasonal variability with increases of air temperature that exceed 5.5°C in the summer and autumn months, with the remaining seasons increases don't exceed 4°C. In the mid-century the seasonal variability is also quite striking, with increases of temperature ranging from 2.5°C in DJF to 4.5°C in JJA. The maximum and minimum air temperatures show nearly identical features in the region.

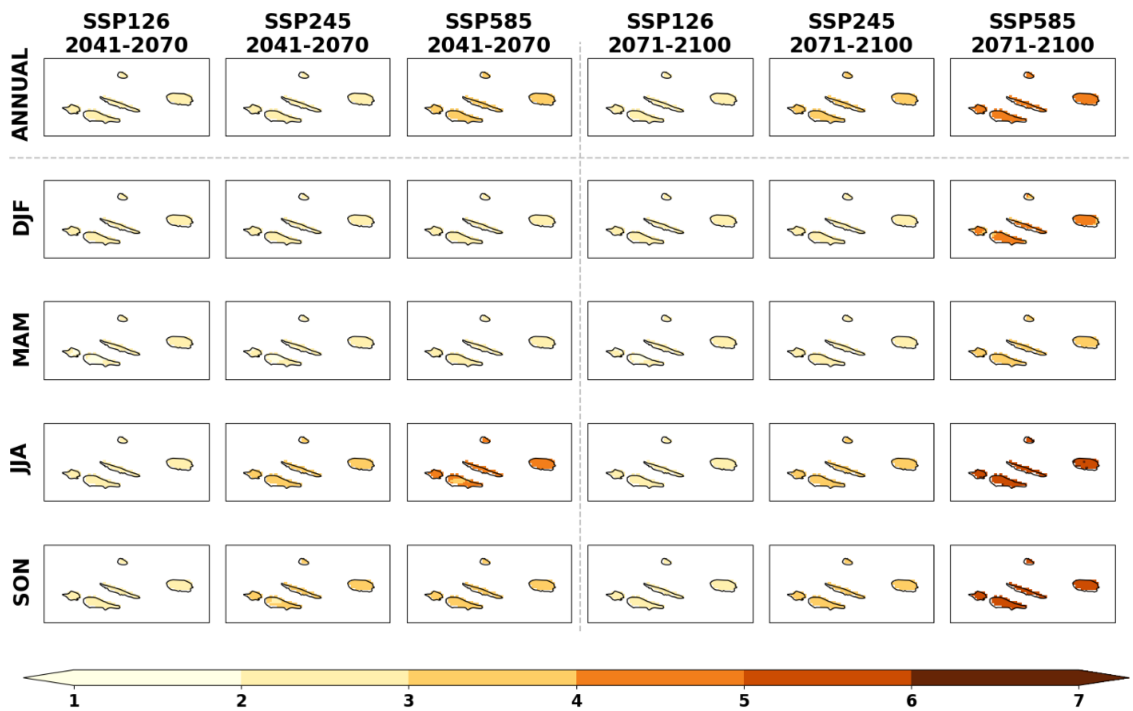

Figure 17 - Future projected changes in daily mean air temperature for the Azores Central Group (Units: °C).

5.2.1.2. Eastern Group

In the Eastern Group both islands show a warming trend. Again, there are not any noteworthy differences between both islands (figure 18).

In the mid-century the warning air temperatures range from 2.4°C in the low emission scenario to 3.3°C in the high emission scenario. By the end of the century however the spread seen in the three scenarios considered here is quite large, with a best-case scenario warming of 2.6°C and in the worst-case scenario of nearly 5°C in both islands of the group.

Again, seasonally, in all scenarios and study periods, the warming trends are larger in the summer and autumn months, this is particularly true in the worst-case scenario in the end of the century period.

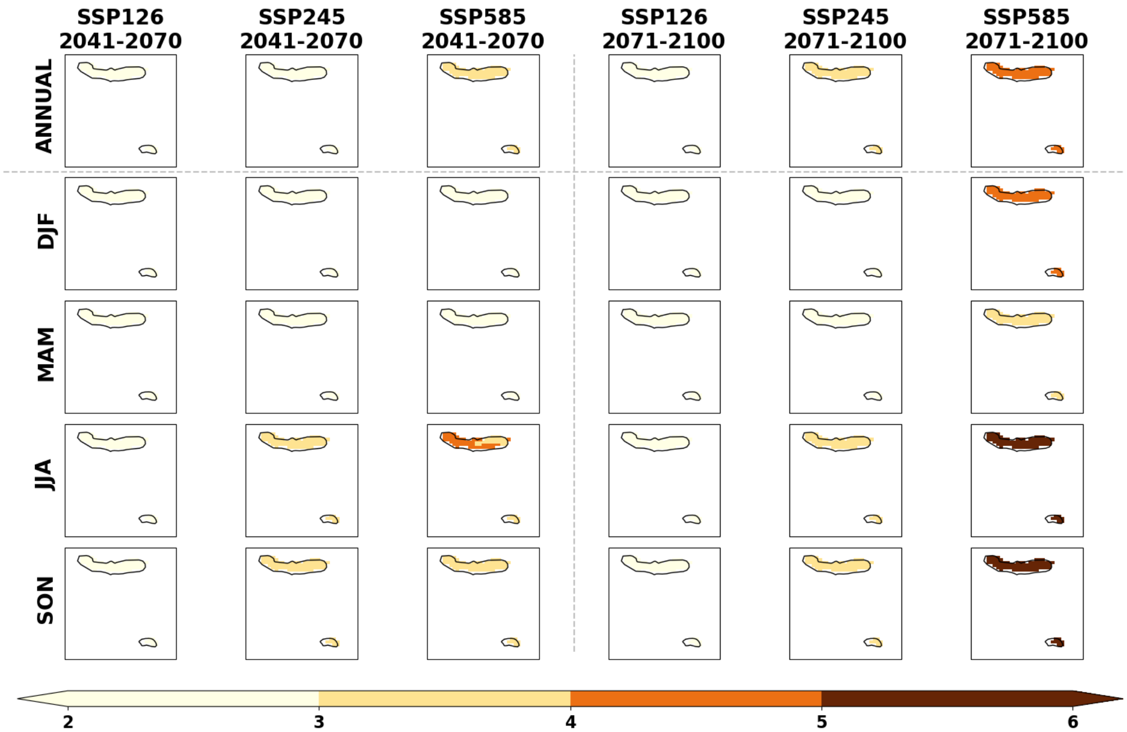

Figure 18 - Future projected changes in daily mean air temperature for the Azores Eastern Group (Units: °C).

5.2.1.3. Western Group

Future projections show a warming anomaly in both Eastern Group Islands in the Azores Archipelago (figure 19). In this case the warming is nearly identical in both islands, for the mid-century period a warming between 2.2 °C in SPP126 and around 3 °C for the worst-case scenario.

By the end of the century the increase of air temperature can go up to 4.5 °C in the SSP585 scenario and is below 2.5 °C in the best-case scenario. The air temperature anomalies show considerable seasonality with high increases in the summer and autumn months and a lower increase in the winter months.

Looking at maximum and minimum air temperatures all these patterns hold true, although the increase in maximum air temperatures is a fraction lower than those of the minimum and mean air temperatures.

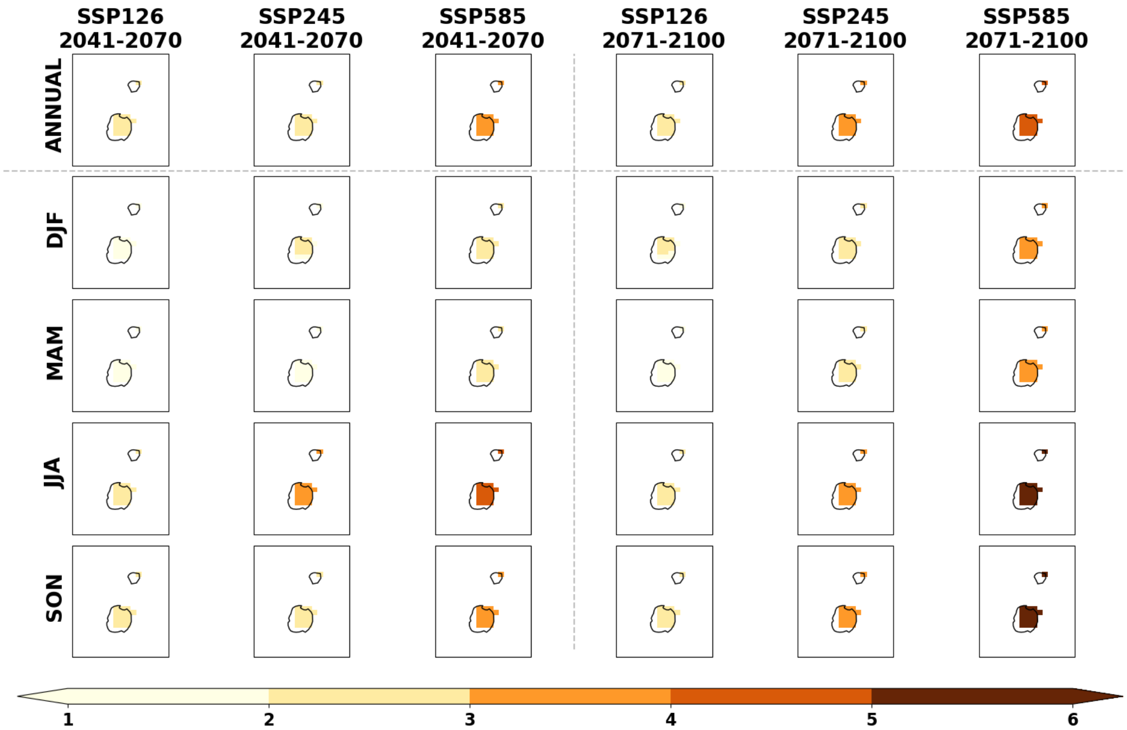

Figure 19 - Future projected changes in daily mean air temperature for the Azores Western Group (Units: °C).

5.2.2. Precipitation

5.2.2.1. Central Group

The total annual precipitation projections for the Central group of the Azores Archipelago are shown in figure 20. Results show only minor differences between the islands, in the mid-century all scenarios projections show an increase of the total precipitation in all the islands with gains of around 0.5mm/day.

By the end-of the century, in the SSP245 the precipitation gains are again around 0.5mm/day, while in the SSP585 scenario in Pico we notice a small loss in the total precipitation. Overall, in all scenarios and time periods the precipitation anomalies are small or negligible.

Seasonally we noticed some variability, with gains of precipitation in DJF in all scenarios and time periods, and minor gains in the spring season. During the summer months results show a general precipitation loss in all the islands with small increases in the Pico Mountain and eastern part of Terceira Island. By the of the century in the SSP585 scenario results point to losses of around 10% in all the islands.

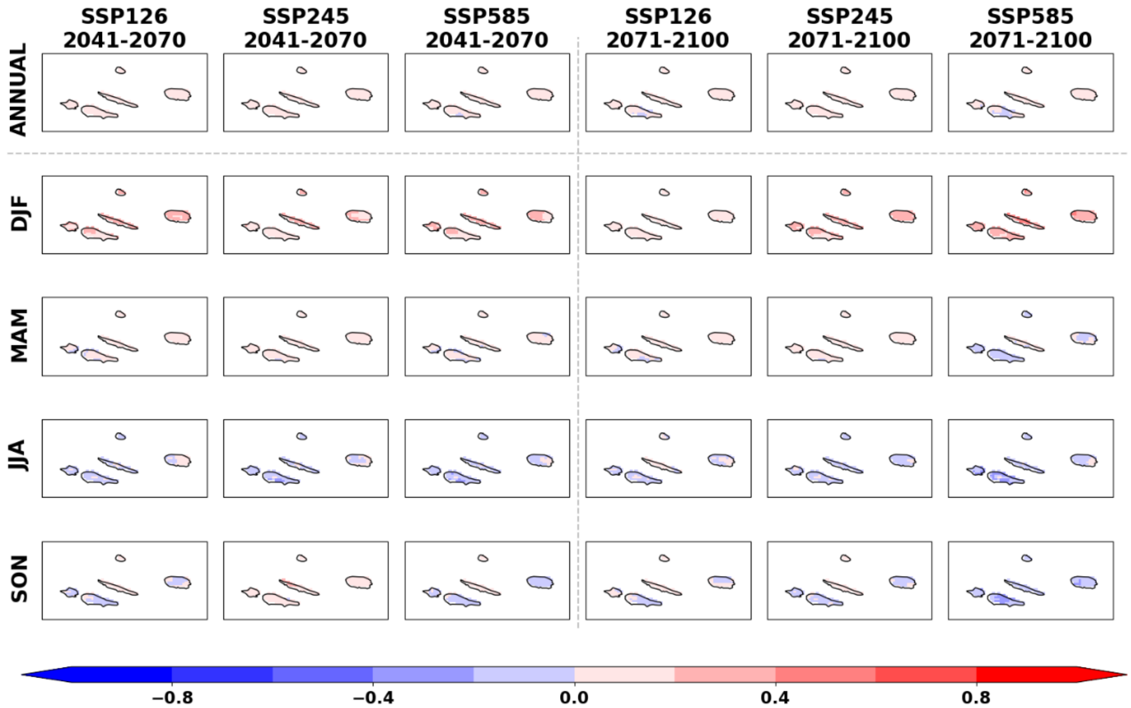

Figure 20 - Future projected changes in total precipitation in the Azores Central Group (Units: %/100).

5.2.2.2. Eastern Group

In the Eastern Group of the Azores Archipelago (figure 21), in the mid-century all scenarios point to a precipitation gain of roughly 10% in all scenarios, but by century end only the SSP126 and SSP245 still show gains in precipitation, in the SSP585 scenario we see almost a zero anomaly in both islands.

Seasonally, the precipitation increases more in the winter months in all periods and scenarios. In the SSP585 scenario by the end of the century mean anomaly over the islands are near zero in the spring and summer months, but there is a considerable loss of precipitation during autumn compensated by gains during the winter months.

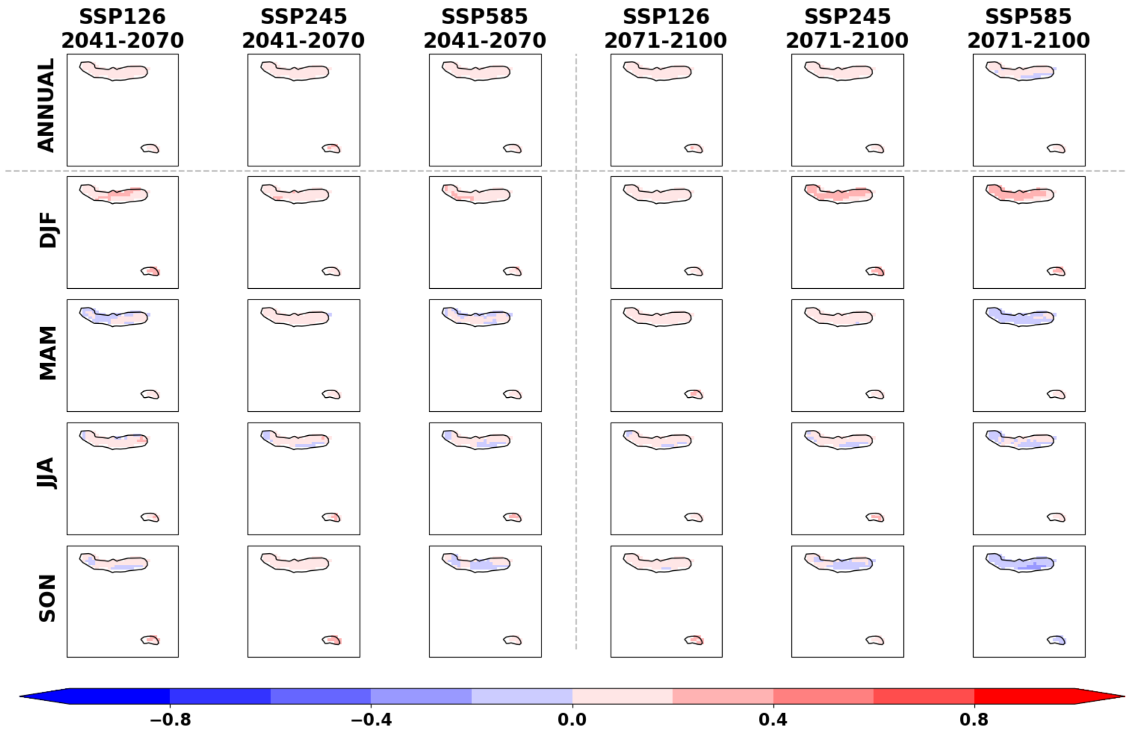

Figure 21 - Future projected changes in total precipitation in Azores Eastern Group (Units: %/100).

5.2.2.3. Western Group

The total annual precipitation in the Western Azores Archipelago (figure 22) shows an increasing trend, for 2041-2070 all scenarios show a gain of precipitation of around 7% and in the end of the century varies between a 3% gain in SSP585 and near a 10% gain in SSP245.

Seasonally during the winter and spring months we notice a large increase in precipitation and a loss of precipitation during autumn (up to 15% in SSP585 in 2071-2100). During the summer months we see a small increase in precipitation in all scenarios and time periods.

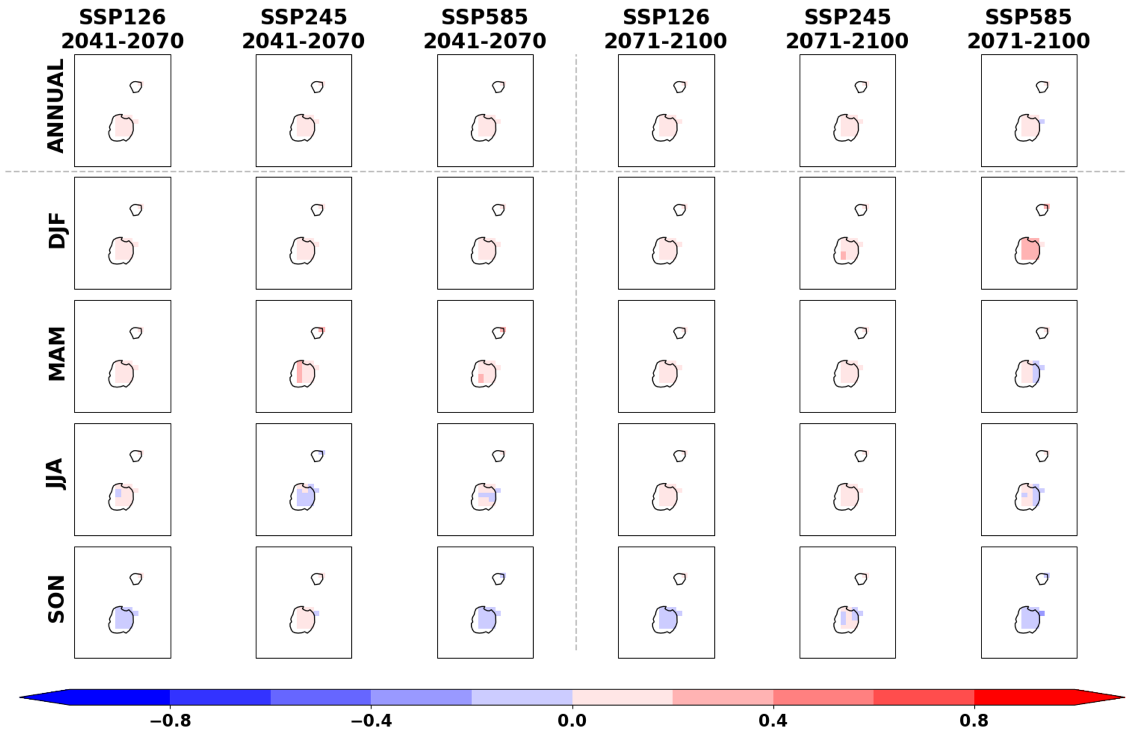

Figure 22 - Future projected changes in total precipitation in Azores Western Group (Units: %/100).

5.2.3. Wind

5.2.3.1. Central Group

In the Central Group of the Azores Archipelago, projections show a decrease in the daily mean wind (figure 23).

The loss of wind is higher in both periods of the SSP585 scenario (near 4%). In the remaining scenarios the losses are around 2% in the SSP126 and 3% in the SSP245. During the winter months projections show an increase of mean wind over the 2041-2070 in all scenarios, in the 2071-2100 period projections show increased wind in the SSP126 and SSP245 scenario, while in the SSP585 on average the mean wind over the islands remains unchanged.

The losses of mean wind in the SSP585 scenario are high in the remaining seasons, particularly in the 2071-2100 period. Overall, losses of mean wind are greater in the summer and autumn months in all scenarios.

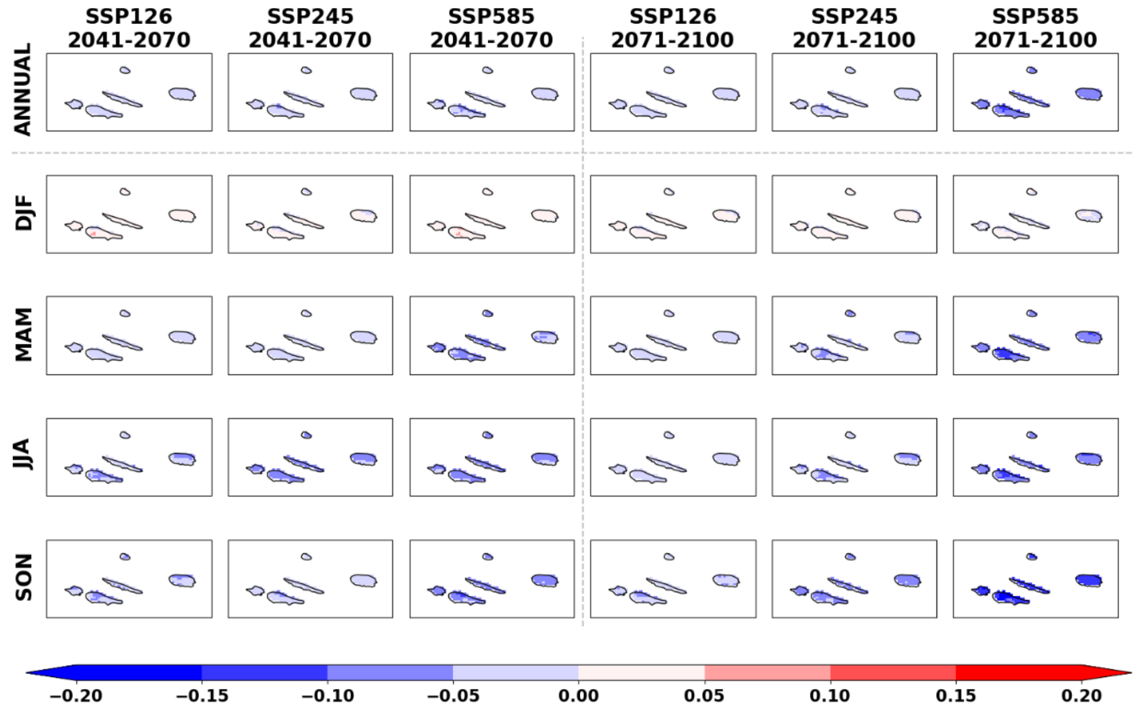

Figure 23 - Future projected changes in daily mean wind speed in the Azores Central Group (Units: %/100).

5.2.3.2. Eastern Group

Looking at the annual mean wind anomalies (figure 24) in the Eastern Group of the Azores Archipelago, we find losses of mean wind ranging from 2-3% in SSP126 and SSP245 scenarios in both time periods, and bigger losses (6-7%) in mean wind in the worst-case scenario in the 2071-2100 period. Seasonally we find small gain in mean wind in the DJF season, and negative anomalies in all remaining seasons.

Losses in mean wind are particularly strong in the 2071-2100 in the worst-case scenario ranging from 10% in the spring months to near 15% in the autumn months. In the SSP126 scenario losses of mean wind are smaller than those found in the SSP245 scenario in the MAM, JJA and SON seasons.

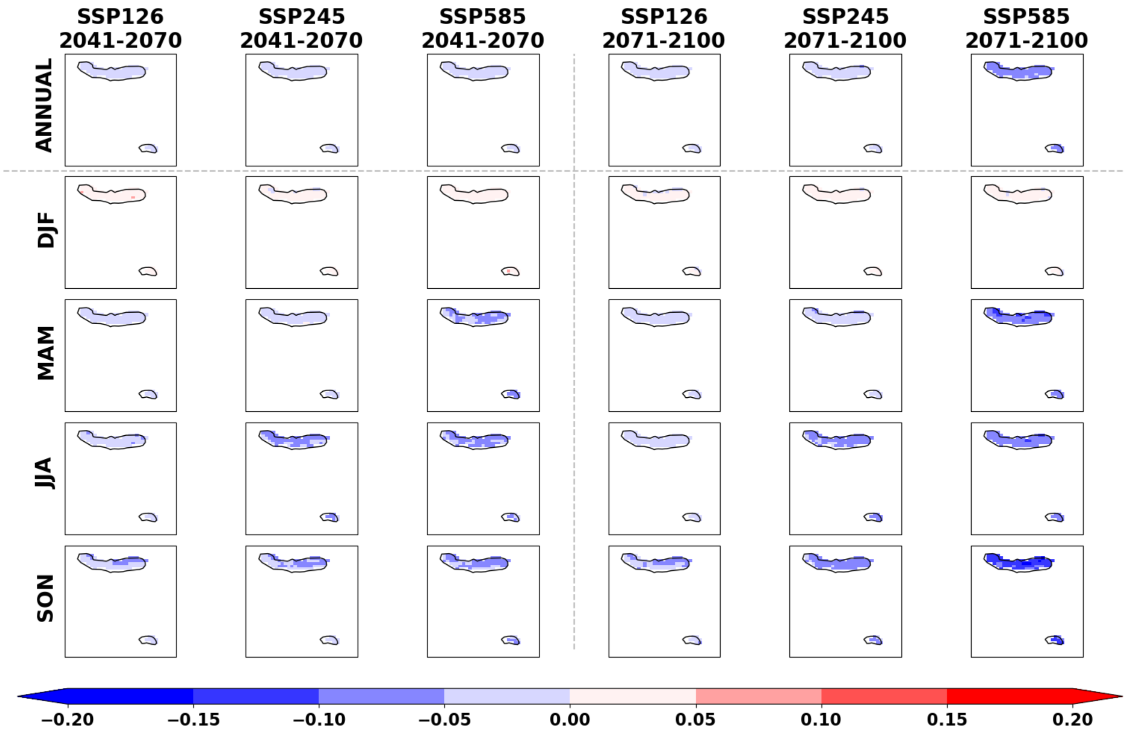

Figure 24 - Future projected changes in daily mean wind speed in the Azores Eastern Group (Units: %/100).

5.2.3.3. Western Group

The changes in 10-meter wind speed showsa decrease of this vital resource for wind energy production (figure 25). In the annual time scale, we find negative anomalies between 4-5% in the mid-century.

This range increases to 3%-9% in the later part of the century. A large part of these losses occurs during the summer and autumn months (maximum of 15% in SSP585 in 2071-2100), during winter the losses are less felt showing a strong seasonality in the wind anomalies.

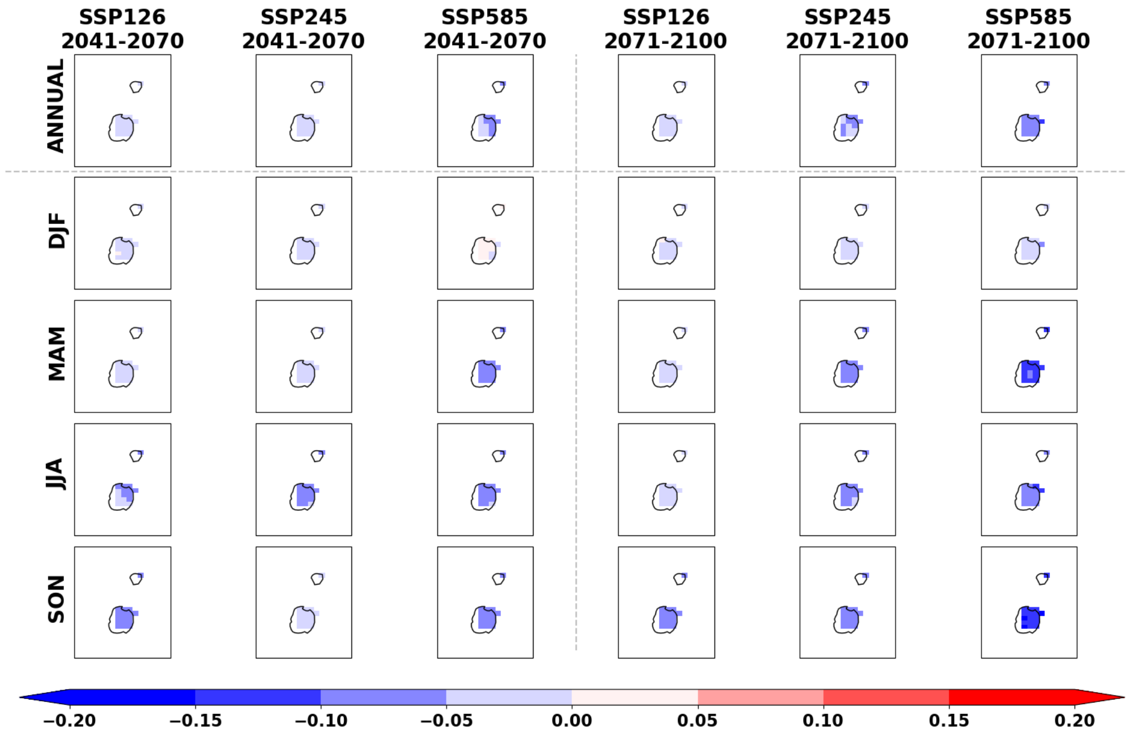

Figure 25 - Future projected changes in daily mean wind speed in Azores Western Group (Units: %/100).

6. Downscaling Climate Extremes and Indices

6.1. Madeira Archipelago

6.1.1. Temperature Extremes and Indices

The diurnal air temperature range anomalies under all scenarios in both study periods show an overall increase in DTR (figure 26), however all results show anomalies below 1°C.

The DTR shows weak seasonal variability, being largest during MAM, JJA, SON, and lower during DJF.In the mid-century period all scenarios show a small decrease of DTR along the southern coastal zone in Madeira Island, this feature is also present in the end-of-century SSP126 scenario. For the SSP245 and SSP585 scenarios DTR show the maximum increases values in the high mountain regions of Madeira and along the western coastal zones. These features are most evident in the SSP585 scenario. In the Porto Santo Island due to its size all DTR anomalies are homogenous throughout the island.

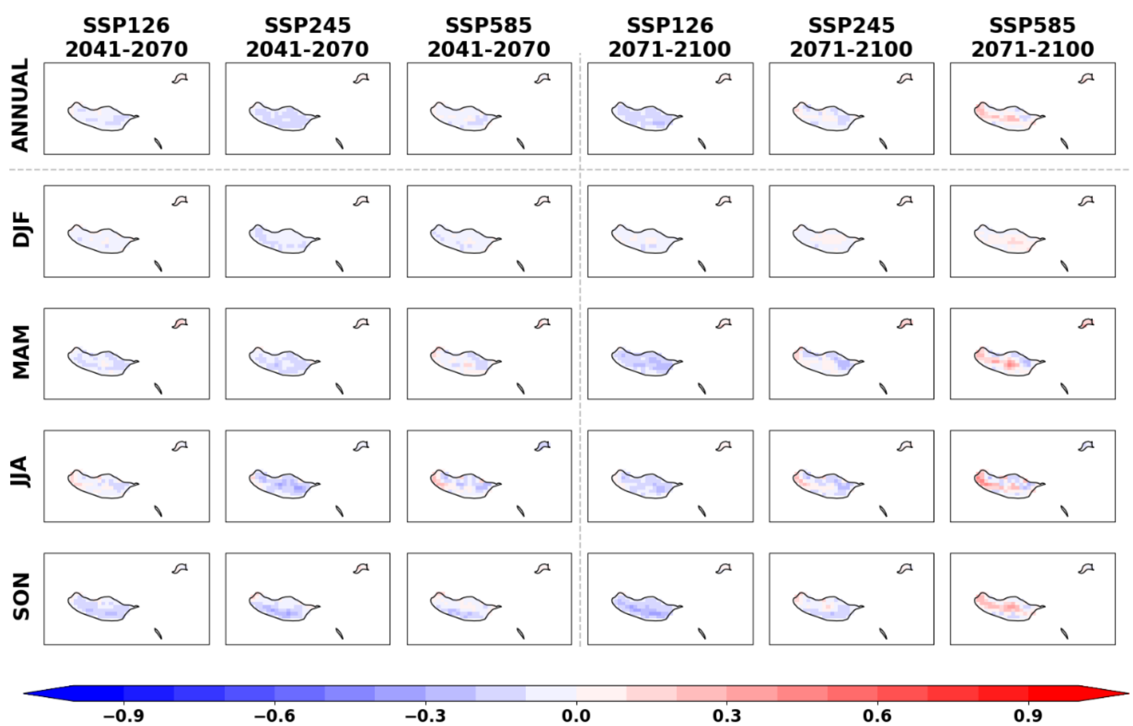

Figure 26 - Future projected changes in daily thermal range in the Madeira Archipelago (Units: °C).

Looking to the average number of days in heatwaves (figure 27) in the mid-century, SSP126 and SSP245 show little changes, in the SSP585 scenario we can see an increase of around 30 days/year in some of the coastal zones in the Madeira Island, these changes occur all during the JJA season. In the end of the century SPP126 again show negligible changes, in the SSP245 scenario some places around the coastal zones show increases of around 30 days/year again occurring only the JJA season. The most significant changes occur in the end-of-century projections in the business-as-usual scenario, all along the coast we show positive anomalies of 30 days/year or greater.

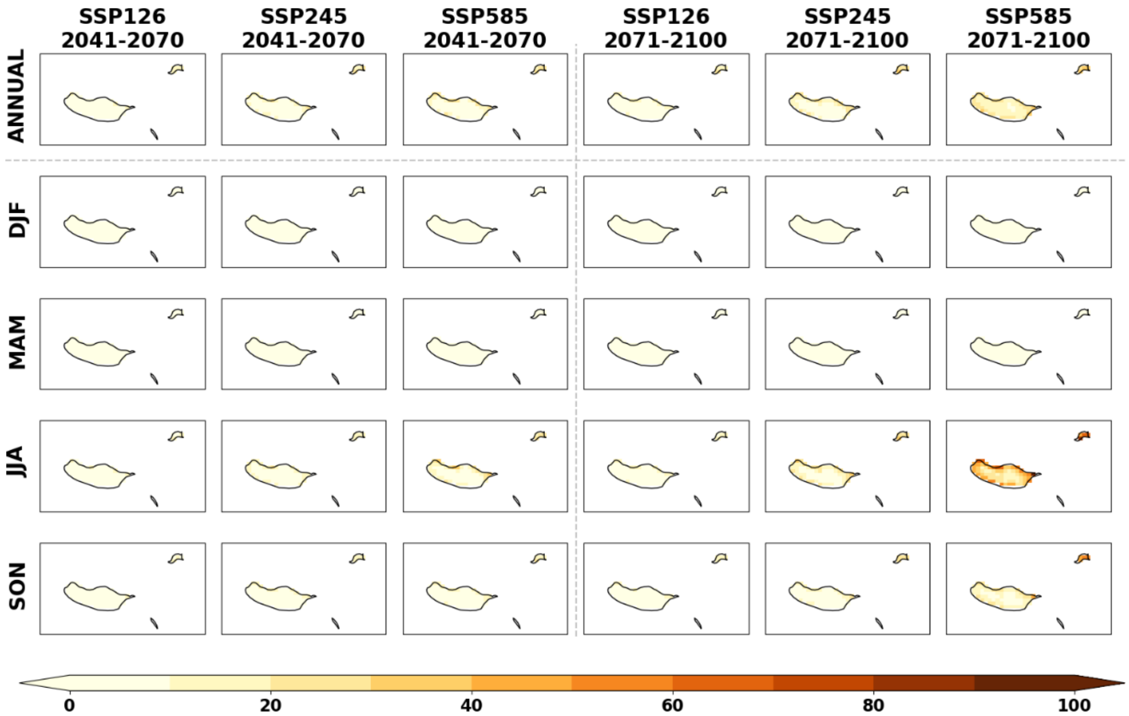

Figure 27 - Future projected changes in the maximum number of days in a heatwave in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The average number of days in coldwaves (figure 28), unsurprisingly show no changes in JJA and SON. In the remaining seasons all scenarios and study periods show a decrease in the number of days. The decrease is strongest in the south coastal zones (around -8 days/year) and weakest in the north coast and high regions in Island of Madeira (around -6 days/year).

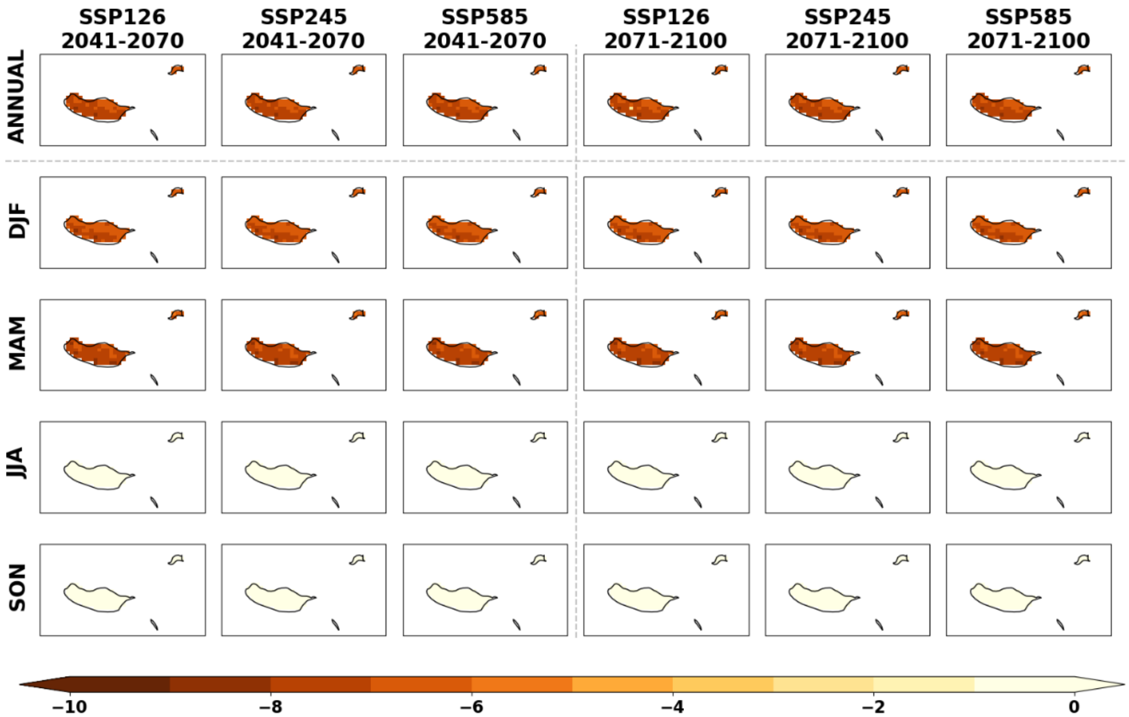

Figure 28 - Future projected changes in the maximum number of days in a coldwave in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The anomalies in the maximum number of days where daily maximum temperature exceeds 35 °C (figure 29) shows positive anomalies particularly in the JJA season. In DJF all scenarios and time periods show no changes, for the MAM season we notice increases of around 2 days/year in the southern coastal regions in both SSP245 and SSP585 by century end. In SON projections shows increases of around 2 days/year in the coastal south region, however in SSP585 scenario for 2071-2100 the anomalies increase in the south coastal and extends almost to the entire island. In JJA we see similar patterns to SON but with increased positive anomalies.

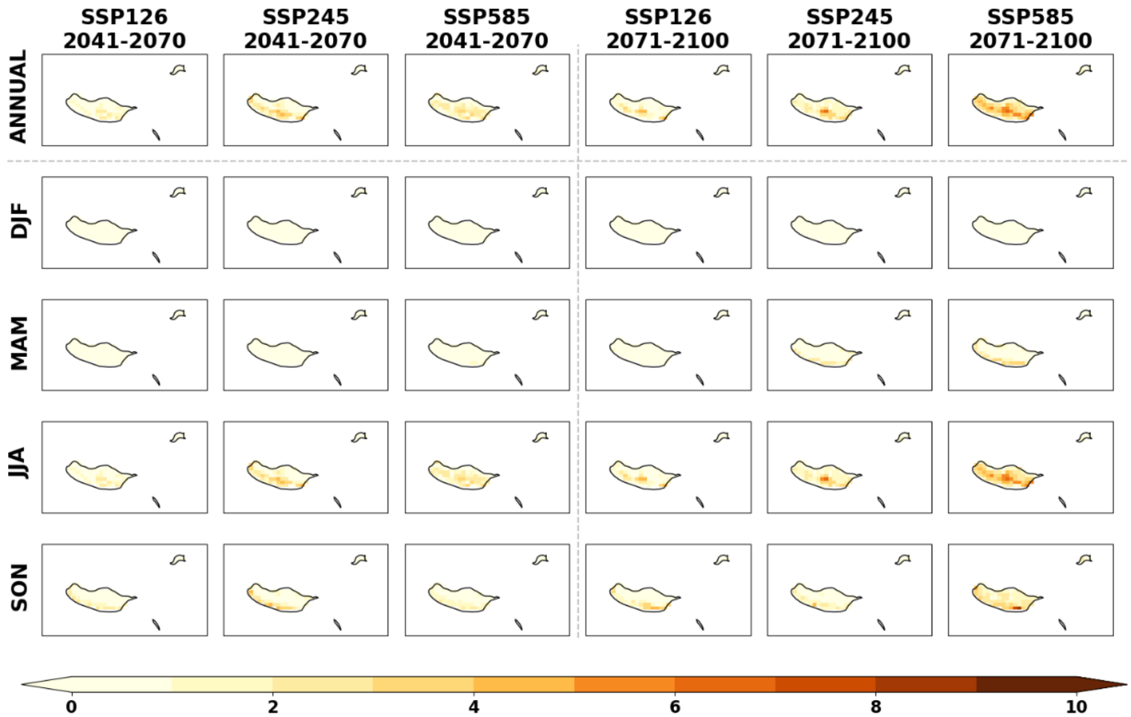

Figure 29 - Future projected changes in the maximum number of consecutive very hot days in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The projections of the number of summer days shows an increase (30 days/year) in the western Madeira coastal zones in both study periods (figure 30). These increases are like the ones we find in the SSP245 scenarios in both periods; however, they are extended to the south coastal regions.

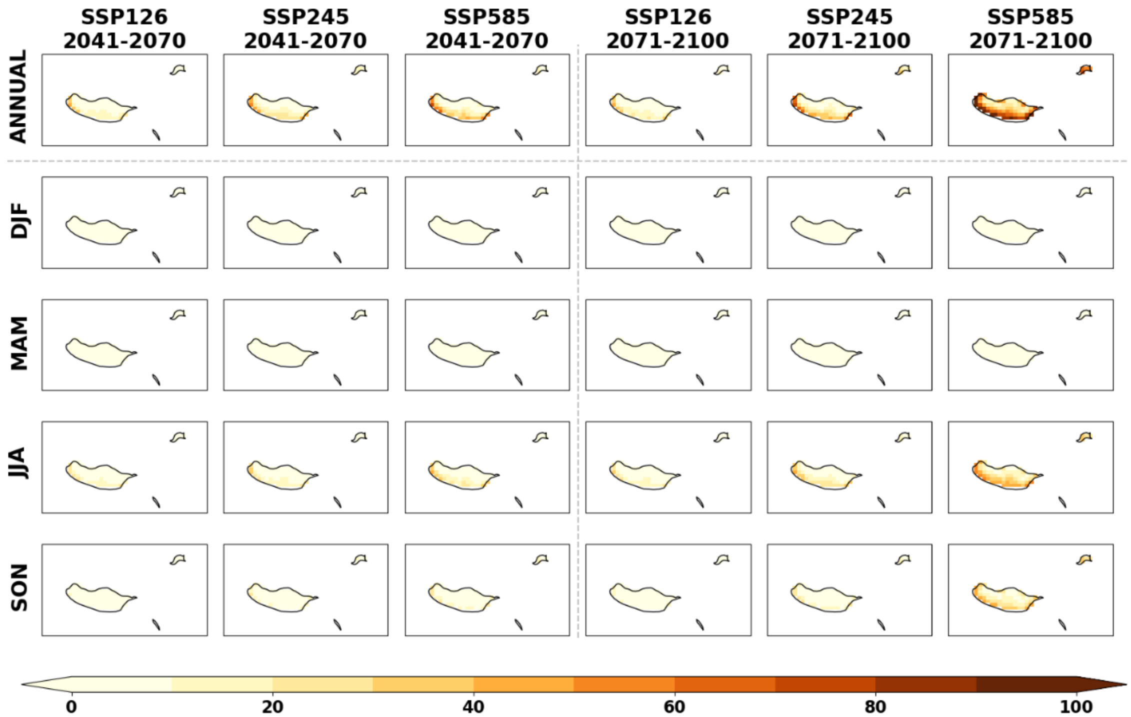

Figure 30 -Future projected changes in the number of summer days in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The largest changes occur in the SSP585 scenarios, in the mid-century the anomalies are larger than those we found in SSP245. In the end of the century anomalies can be as high as 100 days/year all around the coastal south regions, the high regions in Madeira shows increases of 40 days/year and the north coastal regions have smaller positive anomalies. Of course, all these changes occur in the JJA and SON seasons being strongest in the JJA season, during the winter and spring season little of no changes are found. Similar patterns are found in the number of very hot days (figure 31); however, all the positive anomalies are below 3 days/year.

The maximum number of consecutive cold days (figure 32), show strong negative anomalies in all mountains regions in Madeira Island, values range from -60 days/year in the SSP126 for 2041-2070 to values of -100 days/year for 2071-2100 in the business-as-usual scenario. As expected, most of the changes occur during winter and spring seasons and the smallest changes in the summer months.

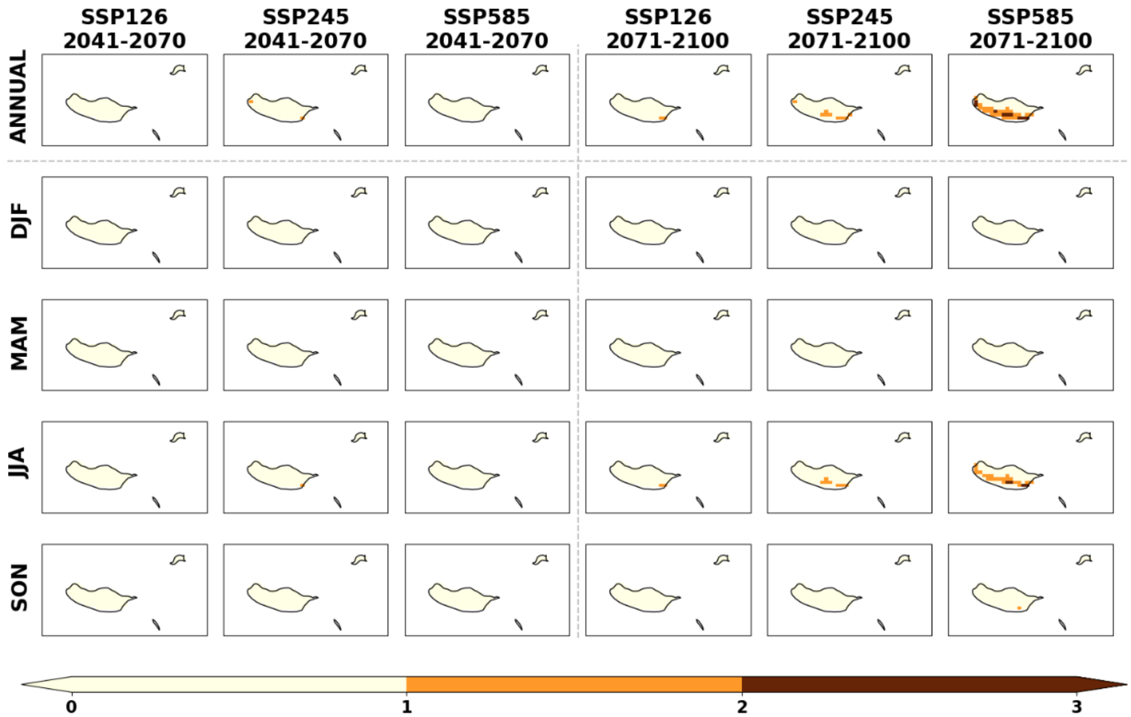

Figure 31 - Future projected changes in the number of very hot days in the Madeira Archipelago (Units: Units: days/year for the annual and days/season for the seasonal).

The number of tropical nights (figure 33) shows almost no anomalies in both periods in the SSP126 scenario. In the medium emissions scenario, no relevance changes are found in the middle of the century, but in the end of the century positive anomalies of 40 days/year can be found in the south coastal regions of the island. In the business-as-usual scenario increases of 40 days/year are also found in the south coastal regions in the 2041-2070 period. By the end of the century, values greater than 80 days/year are found in the south coastal regions, the smallest increases are found in the coastal regions and in the north coastal regions we find values of around 40 days/year. All the changes described above occur during the summer and autumn months, with the remaining months showing no changes.

The projected changes of the number of frost days (figure 34) shows only negative anomalies in the mountainous regions of Madeira Islands, with all anomalies occurring during the winter and spring months.

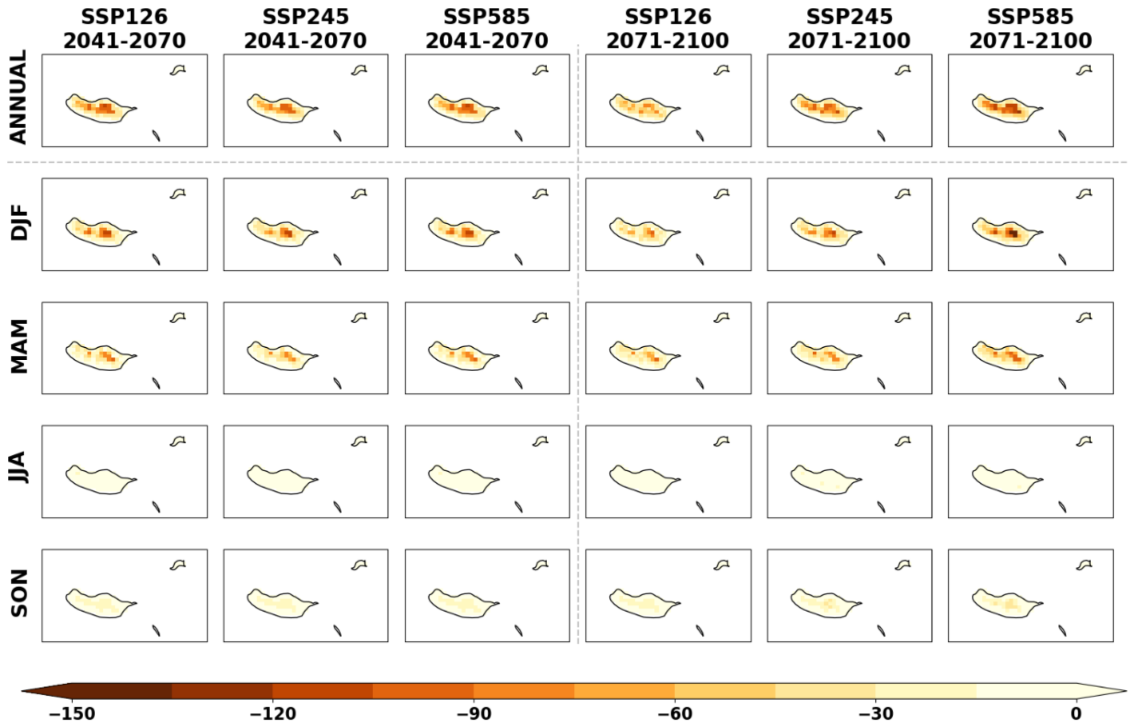

Figure 32 - Future projected changes in the maximum number of consecutive cold days in the MadeiraArchipelago (Units: Units: days/year for the annual and days/season for the seasonal).

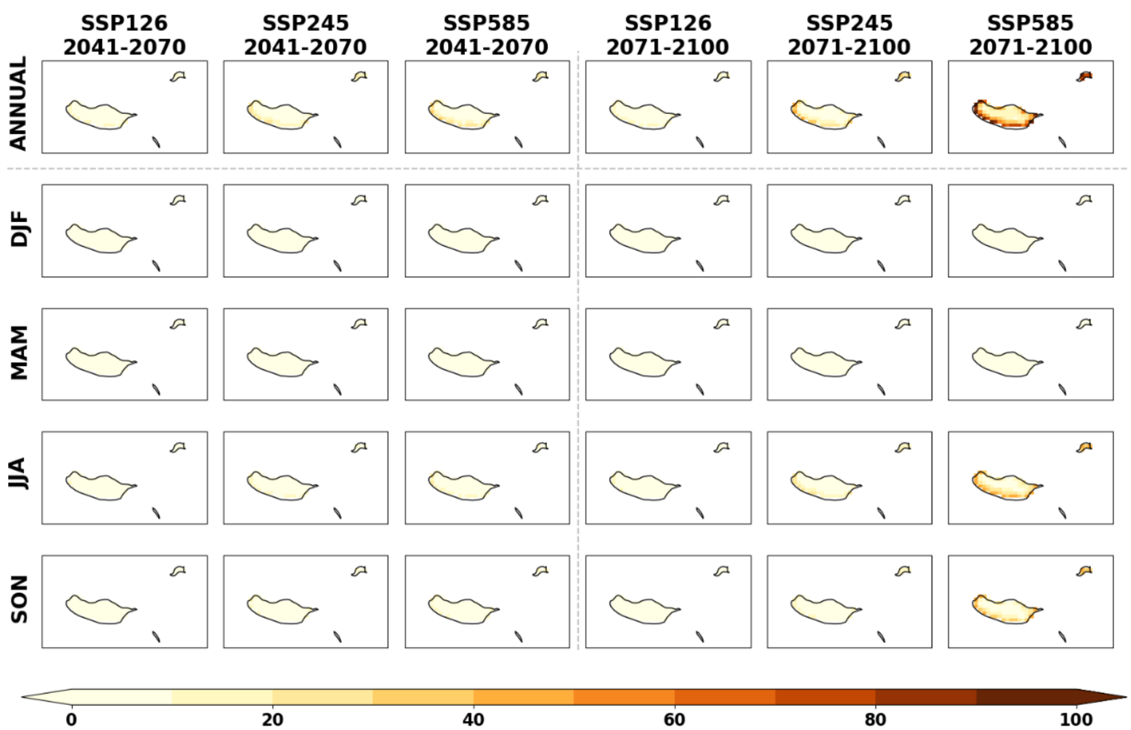

Figure 33 - Future projected changes in the number of tropical nights in the Madeira Archipelago (Units: Units: days/year for the annual and days/season for the seasonal).

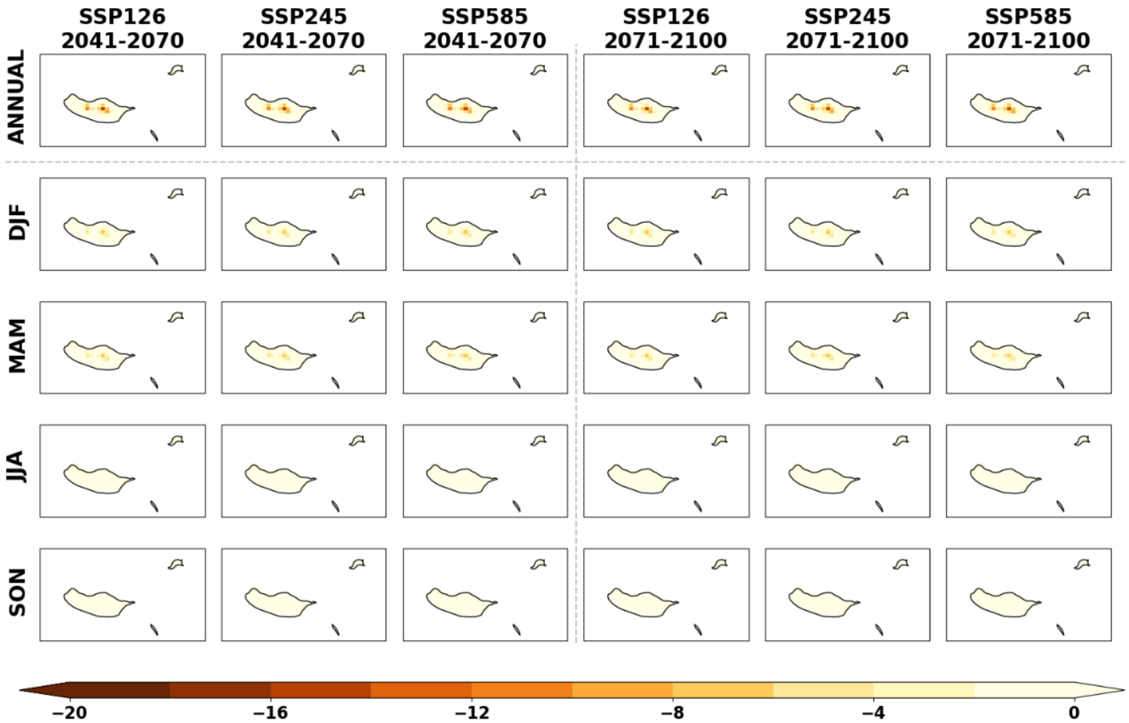

Figure 34 - Future projected changes in the number of frost days in the Madeira Archipelago (Units: Units: days/year for the annual and days/season for the seasonal).

6.1.2. Precipitation Extremes

The projections showed relevant anomalies for the maximum precipitation accumulated over a five-day period (figure 35). For the 2041-2070 period, under the SSP585 scenario we find strong positive anomalies in the eastern mountainous region in Madeira Island with values over 200 mm, in the SSP245 scenarios we again find large positive anomalies in the same region and strong increases in the north coastal regions. In the mid-century for the best-case scenario, we can find positive anomalies of around 100 mm in the mountainous regions. In the end of the century under SSP245 and SSP585 scenarios we find positive anomalies of 100 to 300 mm in all the Madeira high regions with almost no changes in the coastal regions.

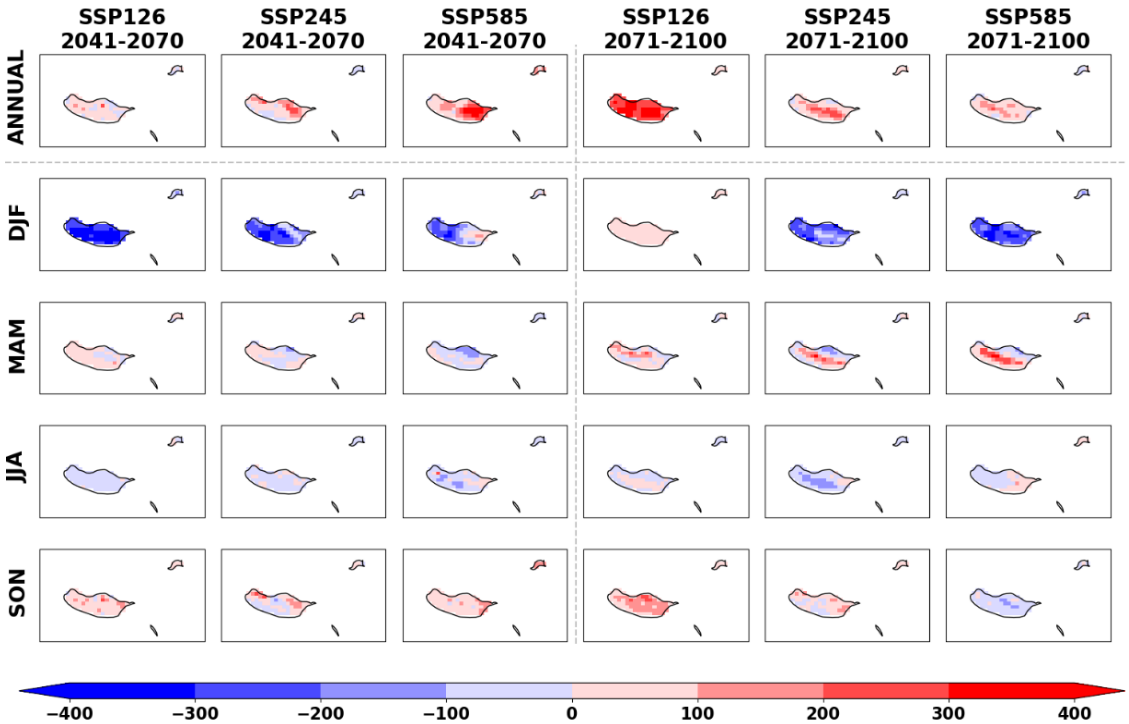

Figure 35 - Future projected changes in maximum cumulative precipitation over a five-day period in the Madeira Archipelago (Units: mm).

Noteworthy is that under the SSP126 scenario in the end of the century we find strong positive anomalies all through Madeira Island with values above 200 mm. Seasonally we find that under SSP126 in the mid-century little or no changes occur, however the remaining mix of scenarios/period we notice strong negative anomalies with stronger signal along the coastal regions. During the JJA season changes only occur under SSP245 in the end of the century with negative anomalies. During both MAM and SON in general all high region of the island shows a positive increase in the total precipitation accumulated over a five-day period.

The projected changes in the number of days with precipitation exceeding 20 mm (figure 36), shows an increase all around the island under the SSP126 scenario by the end of the century during the DJF and SON season (range between 2 and 6 days/year).

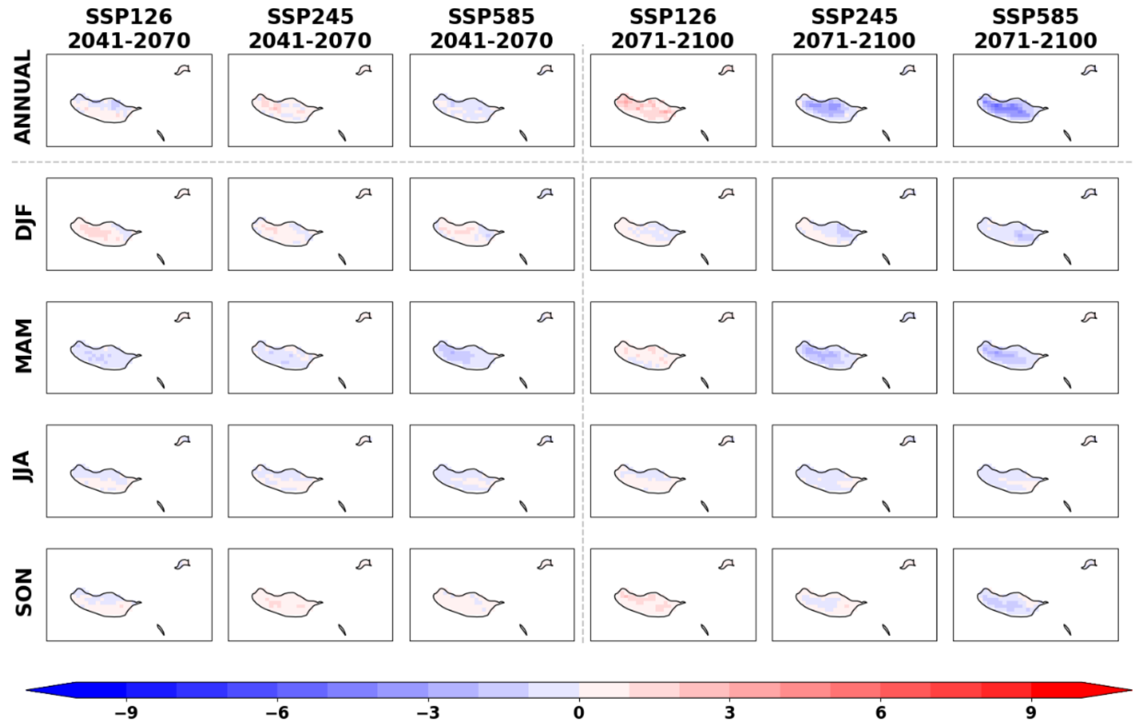

Figure 36 - Future projected changes in the number of days with precipitation exceeding 20 mm in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The number of days shows a negative anomaly under the other two scenarios in the end of the century. This is most noticeable during the winter and autumn months. In the mid-century during the winter and autumn months, we see small increases in the number of days with precipitation over 20 mm/day. During the MAM season generally, we find a small decrease of the number of days, and during summer we find negligible changes in the number of relative heavy rain days.

All the same projections are found in the number of days with precipitation exceeding 10 mm (figure 37), but with higher values ranging from -9 to 9 days/year.

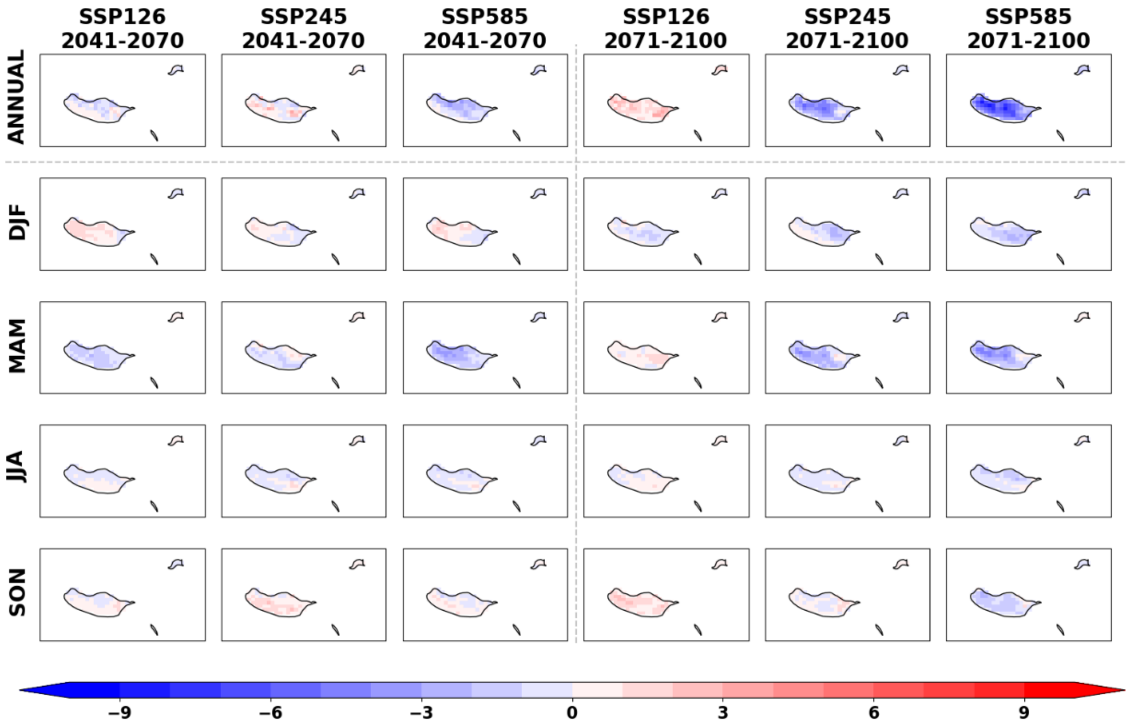

Figure 37 - Future projected changes in the number of days with precipitation exceeding 10 mm in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

Again, the number of days with precipitation exceeding 50 mm/day (figure 38) shares the same patterns with the above projections but with values ranging from -3 to 3 days/year.

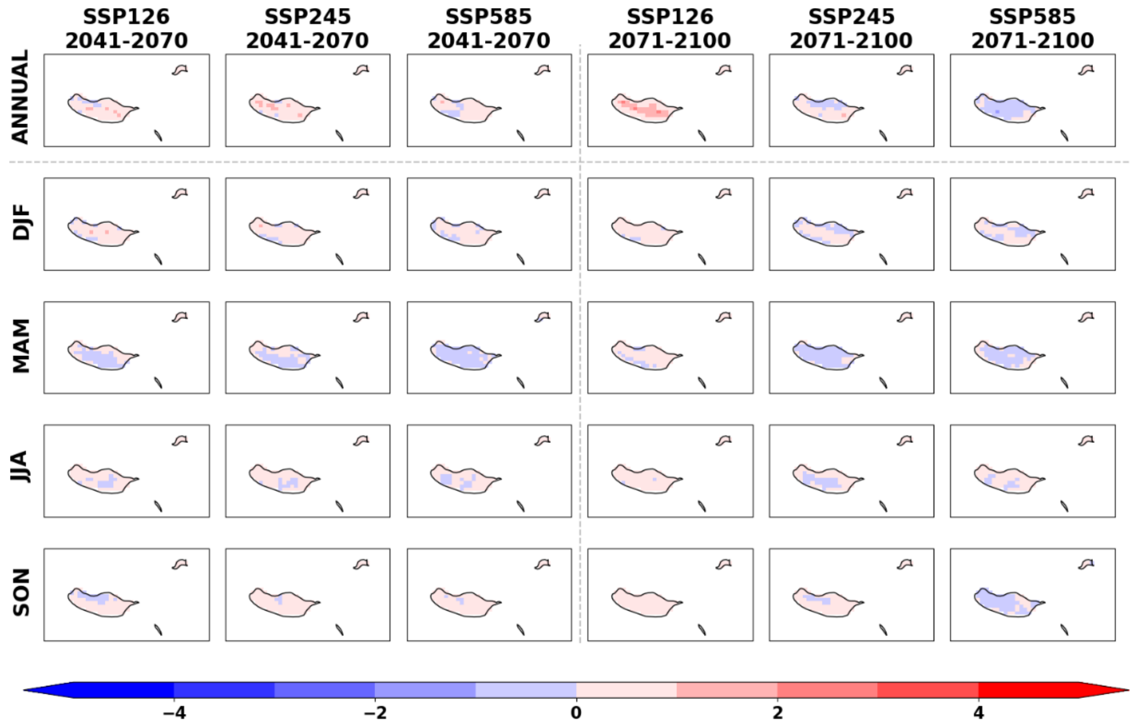

Figure 38 - Future projected changes in the number of days with precipitation exceeding 50 mm in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The number of precipitation days (figure 39) shows negative anomalies in both periods for the business-as-usual scenario with the largest anomalies occurring during spring and autumn.

In the mid-century both SSP126 and SSP245 scenario shows small increase of the precipitation days during all seasons expect during MAM where in general we find small decreases in the southern regions and relatively small increases in the northern part of island. Under SSP126 in 2071-2100 we find increases of the number of precipitation days in all seasons except during DJF that shows near no anomalies.

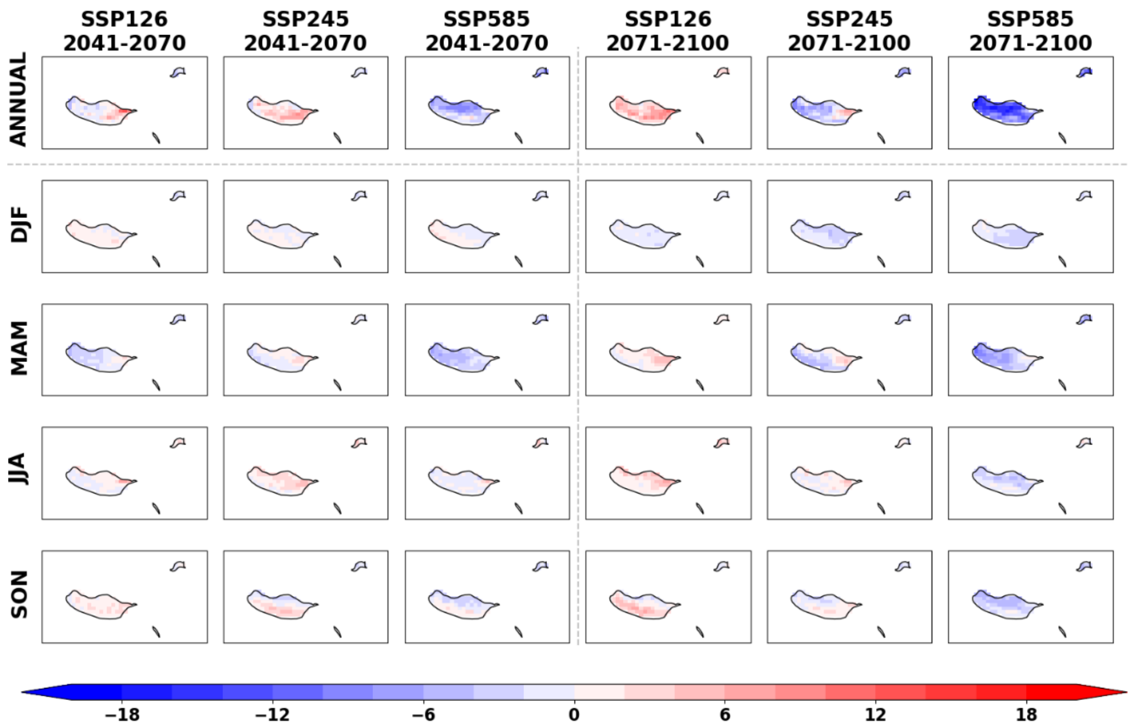

Figure 39 - Future projected changes in the number of days with precipitation exceeding 1 mm in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The average duration of the periods where precipitation exceeds 1 mm/day shows no relevant changes in all scenarios and study periods, with anomalies all falling between -1 to 2 day/year (figure 40).

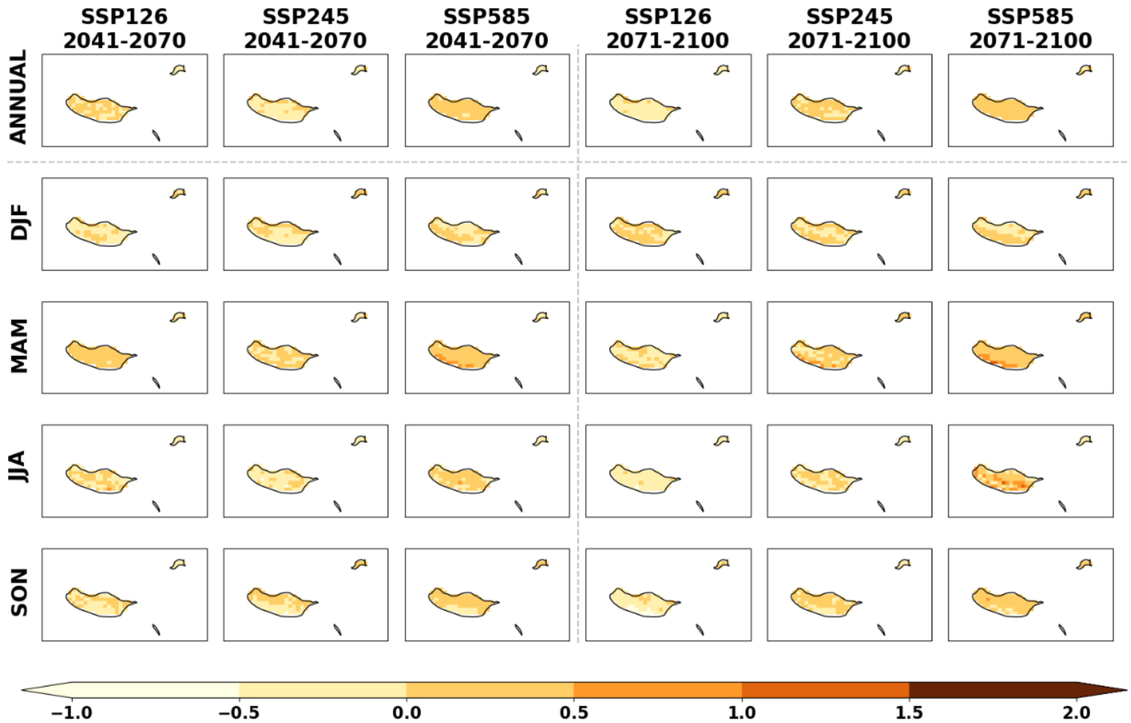

Figure 40 - Future projected changes in average duration of periods where precipitation exceeds 1 mm/day in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

6.1.3. Wind Extremes

The projected number of days with 10-meter wind speed above 5.5 m/s (figure 41) decreases in all the scenarios and periods considered here, the negative anomalies in the mid-century are around 5 days/year and this value rises to values of 15 days/year by the end of the century. Projections also show that the decrease is larger in the high mountains regions that along the coastal regions, and we can also find a positive anomaly (10 days/year) in the eastern coastal region of Madeira in both periods of the SSP585 scenario. Seasonal projections show a small increase in the number of days in the north coast and mountainous regions in Madeira with decreases in the south coastal zones. This north-south gradient is also present during spring and autumn, with negative values all around the island with smaller decreases in the number of days with 10-meter wind greater than 5.5 m/s in the north. During the summer all scenarios and periods point to an increase of wind along the mountainous regions and a strong positive anomaly in the eastern part of the island.

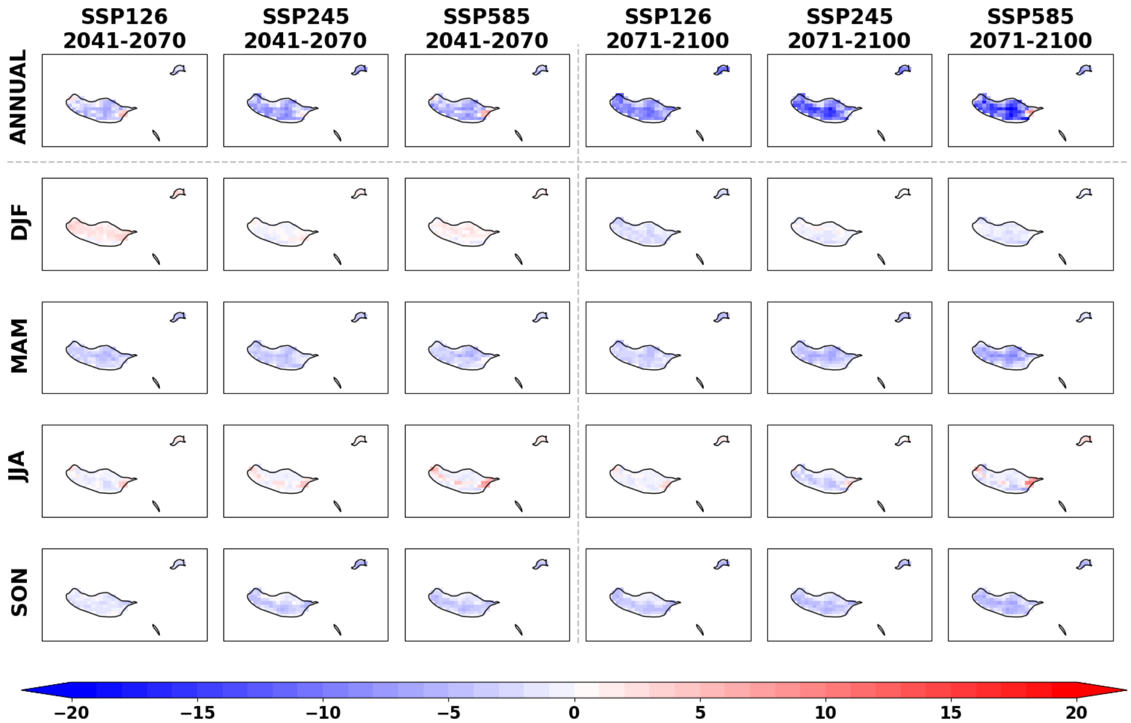

Figure 41 - Future projected changes in the number of days with 10-meter wind speed greater than 5.5m/s in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The number of days with 10-meter wind greater than 10.5 m/s (figure 42) during SON and JJA shows little or no change during all periods and scenarios, during the winter small increases can be found in the centre of the island with no relevance changes found along the coast. In the spring the north-south gradient is present with no changes found along the north region and small decreases in the south coastal regions. Overall, in both periods all scenarios point to negligible changes along the north sector of the island and a small decrease in the number of days in the southern sector of the island.

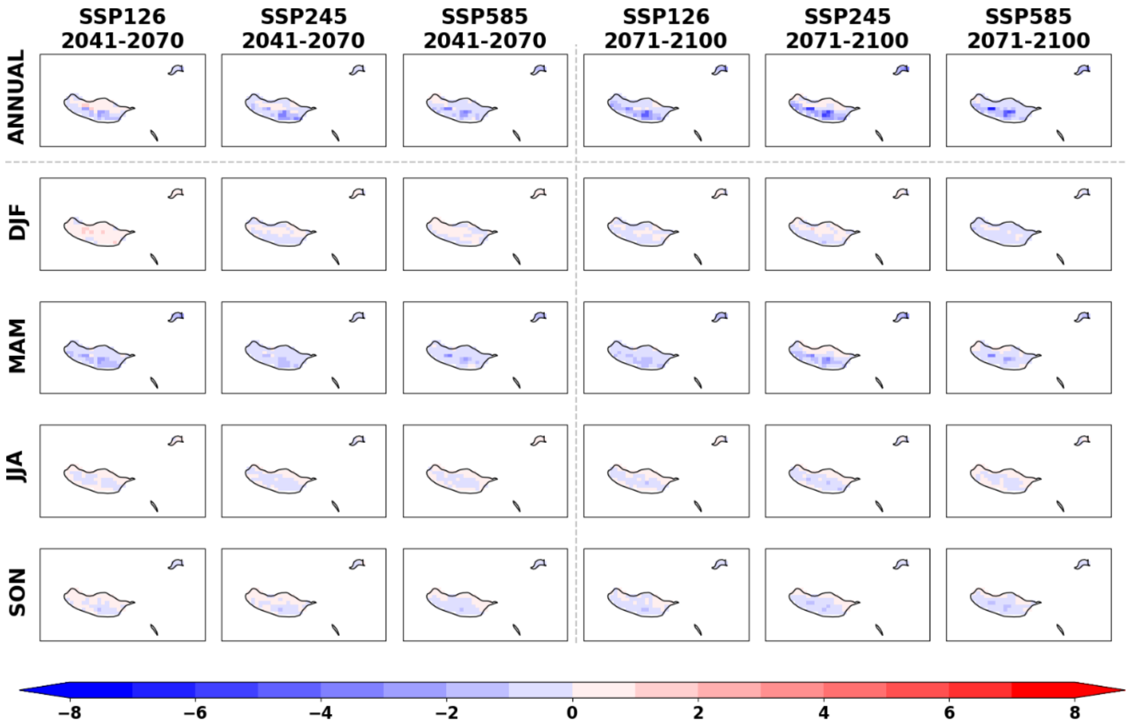

Figure 42 - Future projected changes in the number of days with 10-meter wind speed greater than 10.5m/s in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

The number of calm days (figure 43) increases along São Jorge with values ranging from 15 days/year in SSP126 and SSP245 scenarios to 20-25 days/year in the SSP585 scenario in both time periods (Figure 20). In all cases the remaining island shows anomalies ranging from -5 days/year to 5 days/year. Seasonally during winter, we find no relevant anomalies, most of the changes occur during autumn in all the island gaining from 5 to 10 days/year of no wind days all around the island. During spring and summer no wind days show an increase in the São Jorge district with the remaining island showing small variations either negative or positive.

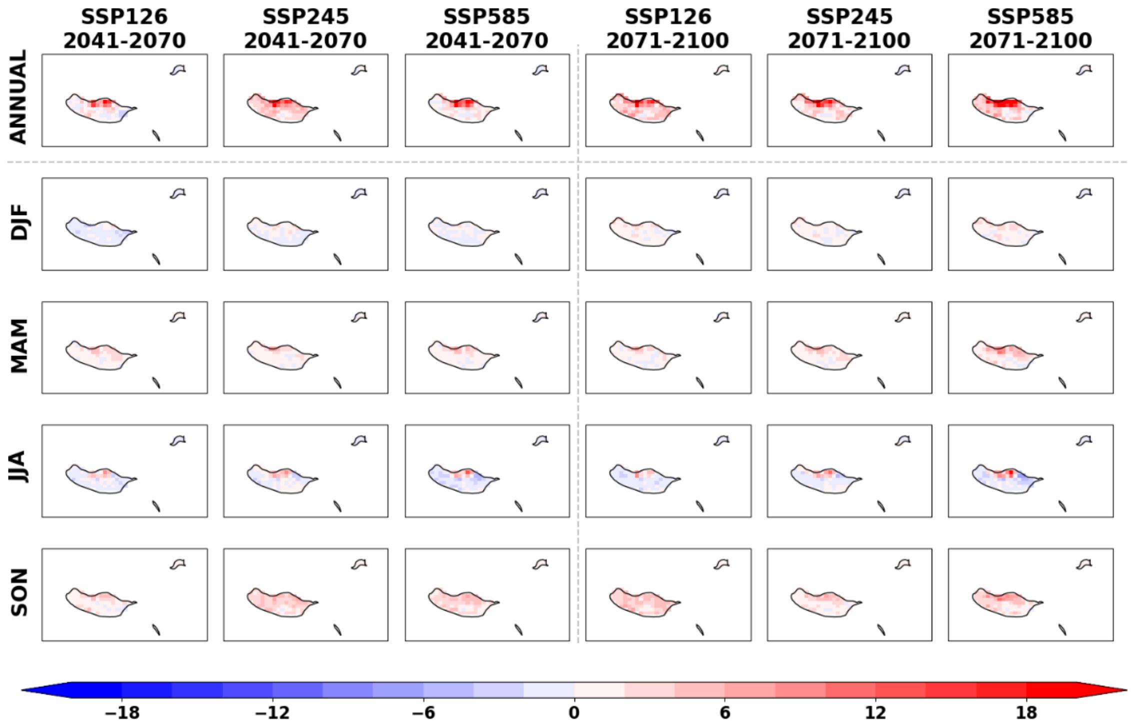

Figure 43 - Future projected changes in the number of days with 10-meter wind speed below 2m/s in the Madeira Archipelago (Units: days/year for the annual and days/season for the seasonal).

6.2. Azores Archipelago

6.2.1. Temperature Extremes and Indices

6.2.1.1. Central Group

In the Central Group of the Azores Archipelago the projected changes in the daily thermalrange (figure 44) in all scenarios and time periods are almost negligible, the only noteworthy mention is the shortening of the DTR in the Pico Mountain in the JJA season. Overall, in all scenarios and time periods, there is a reduction below -0.2°C.

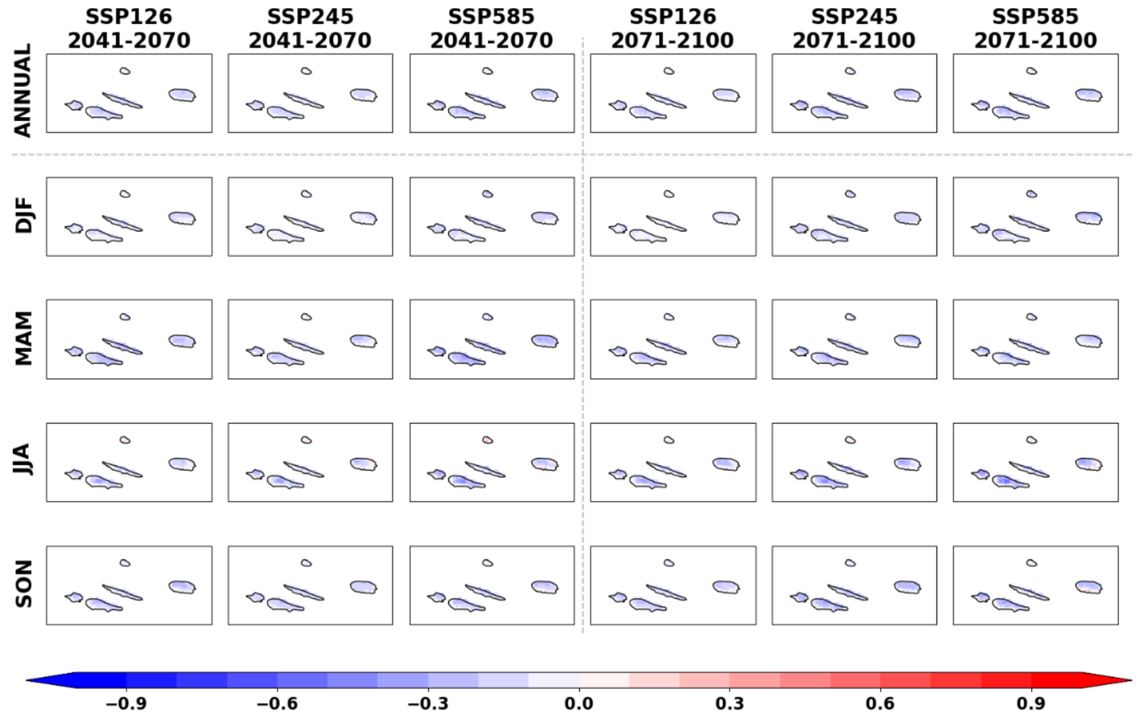

Figure 44 - Future projected changes in the daily thermal range in the Azores Central Group (Units: Units: days/year for the annual and days/season for the seasonal).

The number of days in a heatwave (figure 45) shows little to no change in the winter and spring months.During summer however the number of days in a heatwave increases in all scenarios particularly along the coastal regions. This increase in particularly high in the SSP585 scenario in the 2071-2100 period during the summer, where along the southern coastal region in all the islands increases can be as high as 60 days/year.

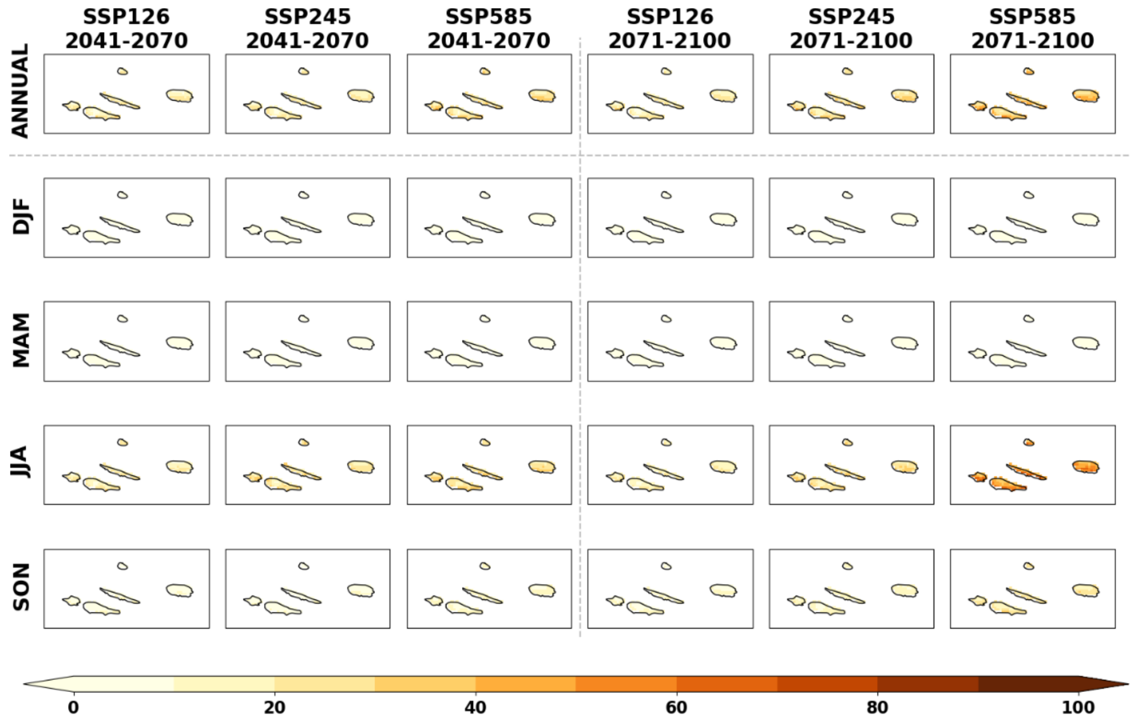

Figure 45 - Future projected changes in the number of days in a heatwave in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

The number of days in a coldwave (figure 46), shows no anomalies in the summer and autumn, during the winter and spring months we can find decreases of around 5-6 days/year in all the islands regardless of period and scenario. Also, one should notice that during these months the changes around the Pico Mountain are almost negligible (below 1 day/year).

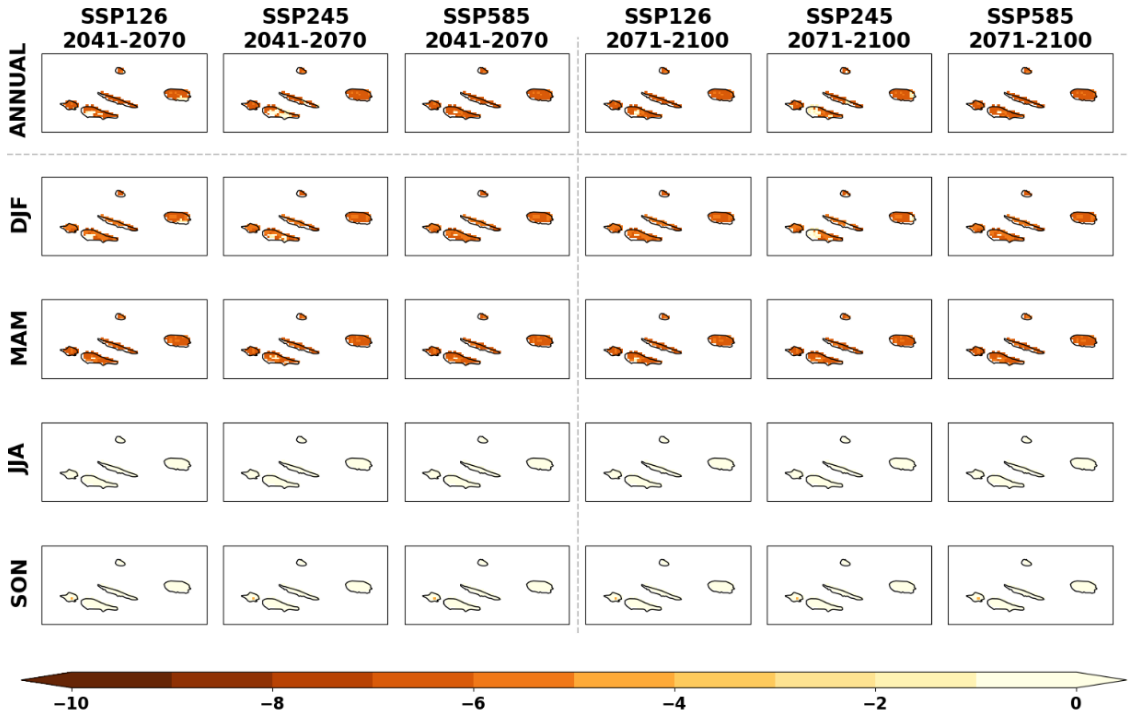

Figure 46 - Future projected changes in the number of days in a coldwave in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

The number of hot days (figure 47), in all the islands shows no anomalies in the mid-century and in the end of the century we can only detect positive anomalies in the SSP585 scenario. These positive anomalies are almost all located along the south coastal regions on all islands and can go as high as 10 days/year.

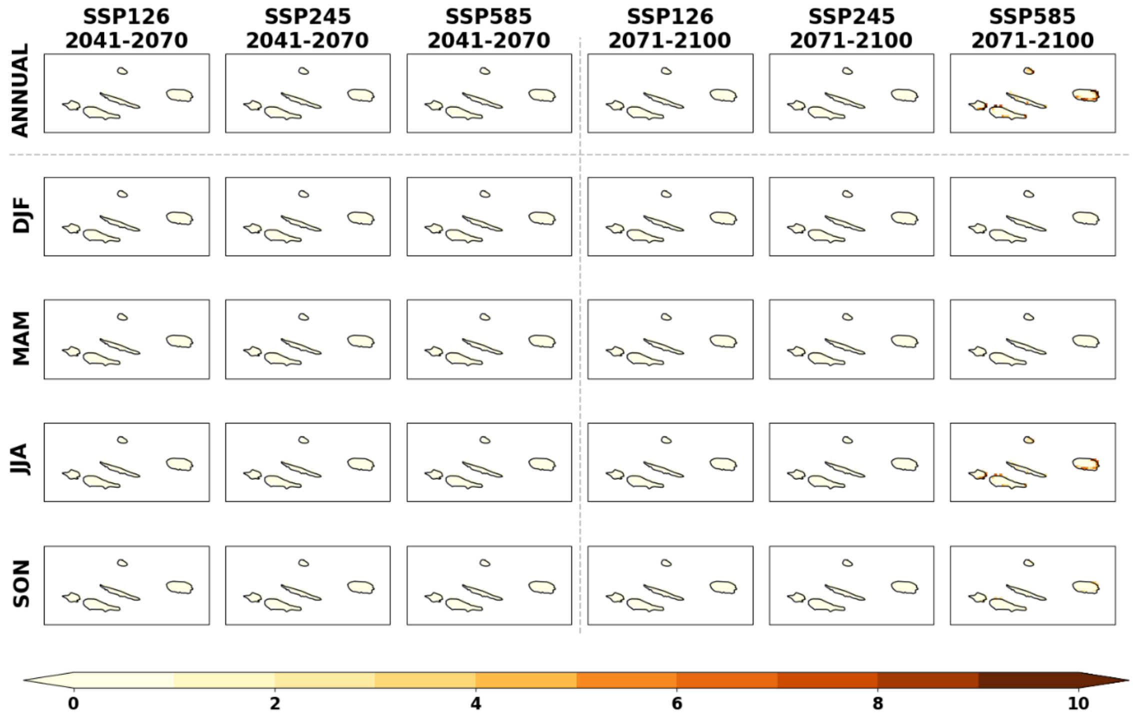

Figure 47 - Future projected changes in the number of very hot days in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

Looking at the summer days (figure 48), in the SSP126 scenario no anomalies are found, in the SSP245 scenario we find increases of the number of days along the coastal regions during the summer months. In the SS585 no anomalies are found in the winter and summer, during the summer however again along the coastal regions we can find strong increases of the number of summer days which can reach 50-60 days/year. Overall, under the SSP585 scenario for the period 2071-2100 one can expect a greater number of summer days during the year.

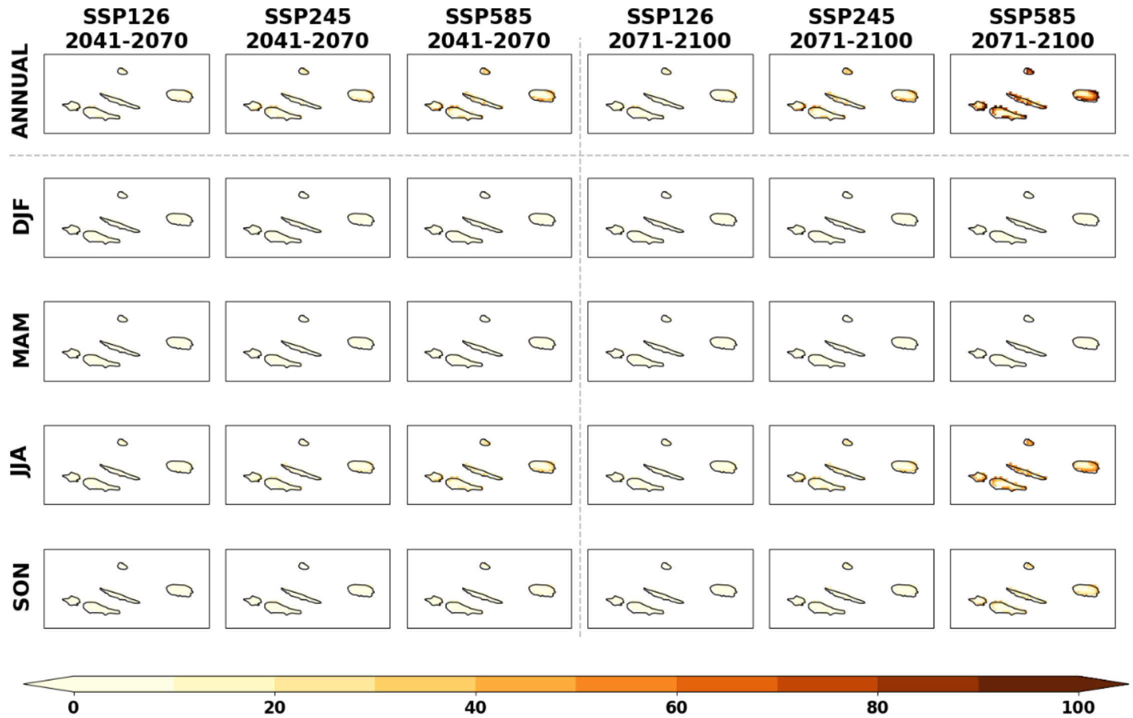

Figure 48 - Future projected changes in the number of summer days in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

Most of what we said about the number of summer days can be repeated for the number of tropical nights (figure 49). No changes occur during the winter and spring months, and during the summer all along the coastal regions the number of tropical nights increases significantly at 50-60 days/year.

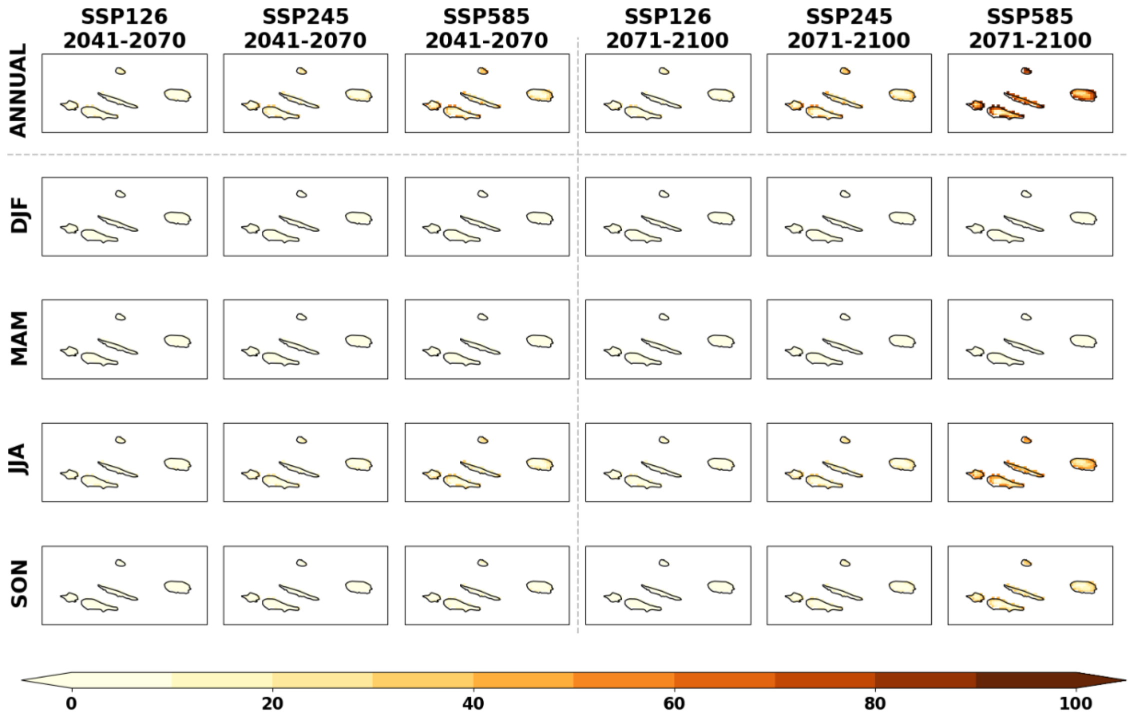

Figure 49 - Future projected changes in the number of tropical nights in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

The number of frost days (figure 50) remains largely unchanged in all islands, but we should note that the number in frost days in the Pico Mountains drops between 20 to 40 days/year in all the scenarios and time periods under consideration.

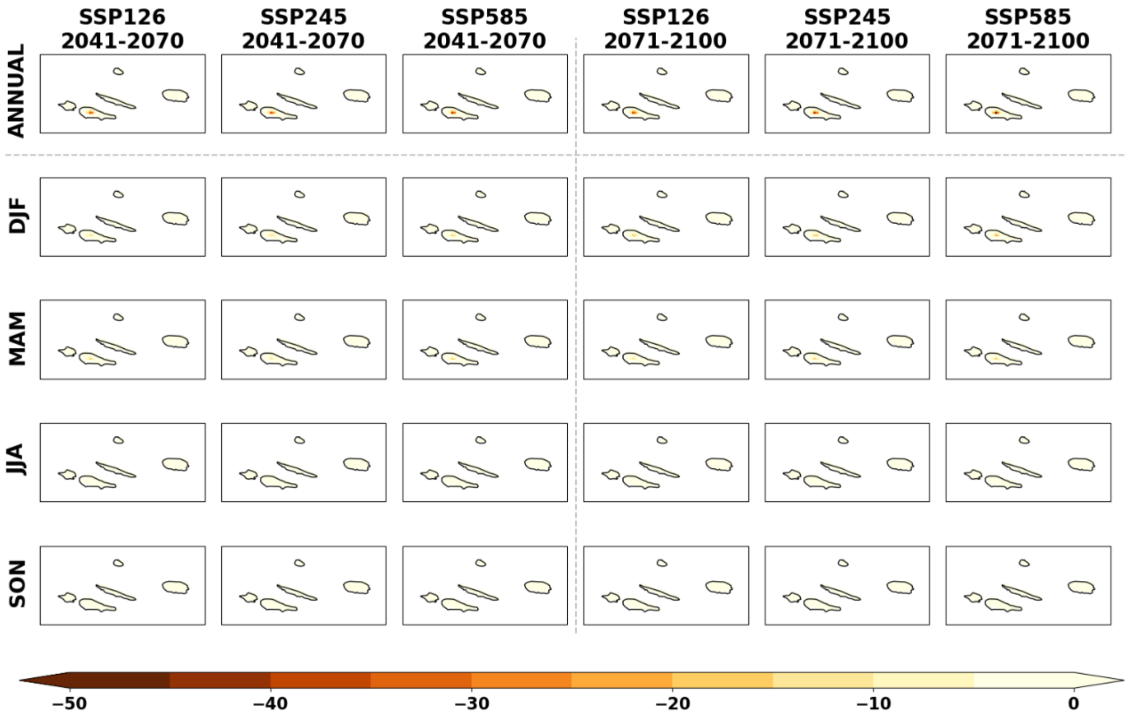

Figure 50 - Future projected changes in the number of frost days in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

6.2.1.2. Western Group

In the Western Group of the Azores Archipelago the anomalies of thermal daily range (figure 51) are in general below -0.2°C in all scenarios and periods, however we should point out that in the Ponta Delgada region in São Miguel Island, we find positive anomalies that can reach 0.2°C in all scenarios and periods under evaluation during the summer months. Like expected the number of days in a heatwave (figure 52) shows no changes during the winter and spring months, during the autumn months we can find anomalies in SSP585 during 2071-2100 period (around 30 days/year), the remaining scenarios and periods show moderate increases in the number of days during a heatwave (near or below 10 days/year). The biggest anomalies can be found in the summer months, this is particularly under the worst-case scenario in the end of the century. The number of days in a coldwave (figure 53) shows only small negative anomalies, all of course, coming from the winter and spring months with these anomalies ranging between -5 to -6 days/year annually.

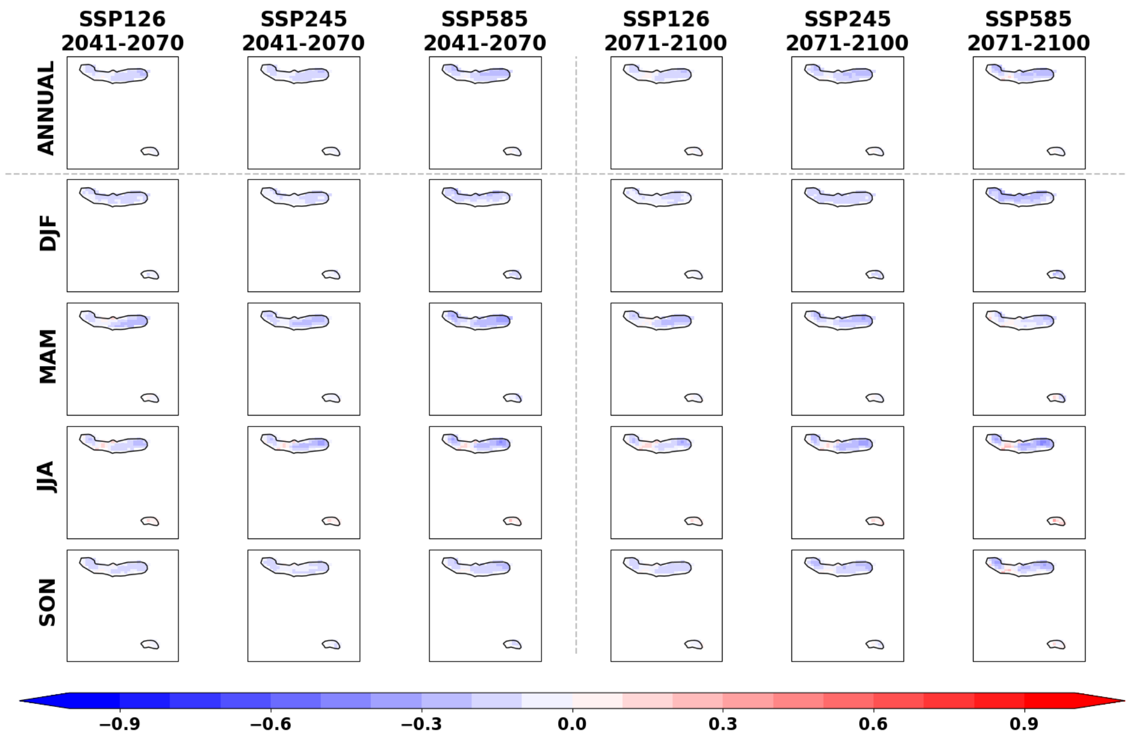

Figure 51 - Future projected changes in daily thermal range in the Azores Eastern Group (Units: °C).

The number of hot days shows almost no anomalies in all scenarios and periods (figure 54); however, a positive anomaly (10-12 days/year) can be found around the Pico da Pedra region in São Miguel Island in the worst-case scenario in the 2071-2100, with the anomalies mostly coming from the summer months. The number of summer days (figure 55) shows no anomalies during the winter and spring months, during autumn in the 2041-2070 period we can only find a small positive anomaly in the Pico da Pedra in São Miguel islands with values below 20 days/year in the SSP245 and SSP585 scenario. Still in the autumn months during the 2071-2100 positive anomalies can be found in Santa Maria only in the worst-case scenario. In São Miguel in 2071-2100 period near no anomalies are found in the SSP126 scenario, for the SSP245 again we see a positive increase in the number of days in the Pico da Pedra region (below 20 days/year) and in the worst-case then increase of the number of summer days in de Pico da Pedra can increase by 40 days/year. In the summer all scenarios show an increase of the number of summer days in Pico da Pedra region in São Miguel Island, during the 2041-2070 the increase varies between 20 days/year (SSP126) to 40 days/year (SSP585). By the end of the century, the anomalies increase in the SSP245 and SSP585, with the latter getting more 50-70 days/year of summer days.

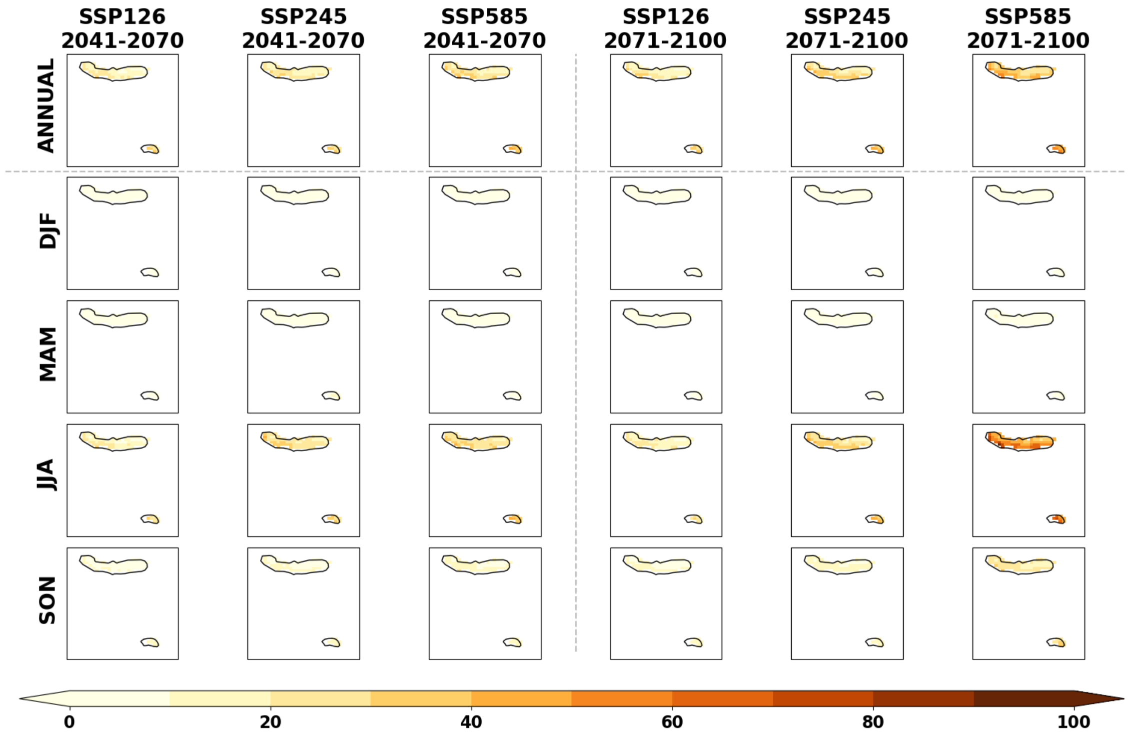

Figure 52 - Future projected changes in the number of days in a heatwave in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

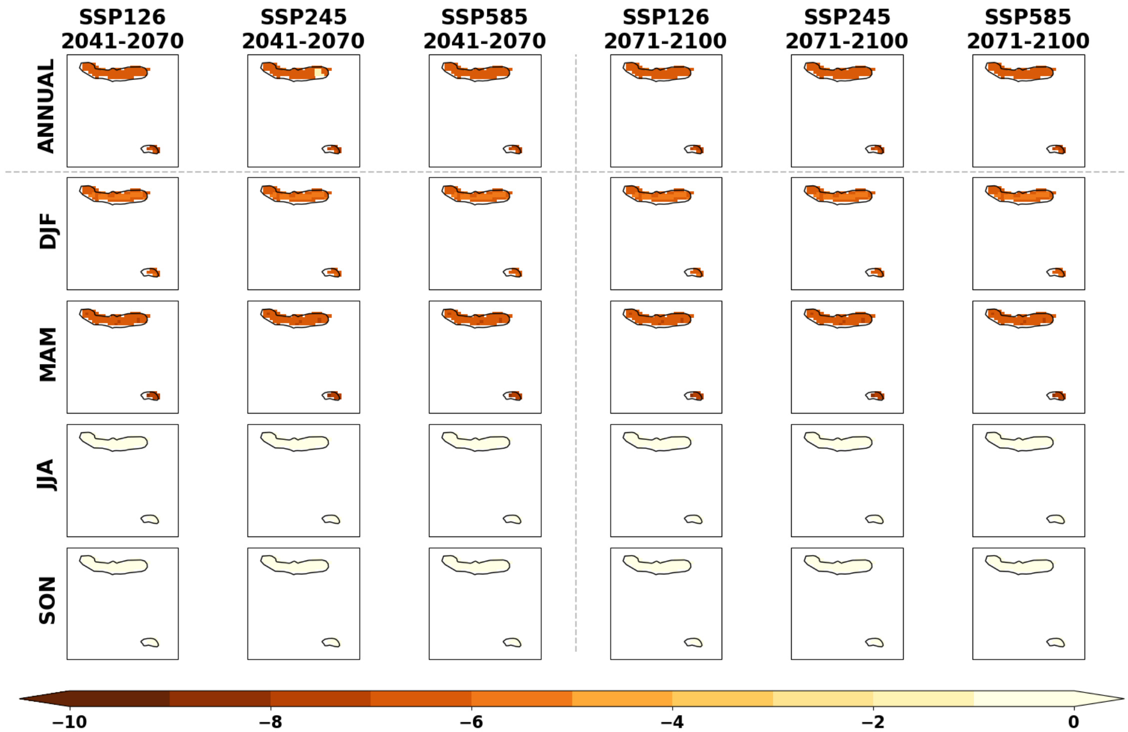

Figure 53 - Future projected changes in the number of days in a coldwave in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

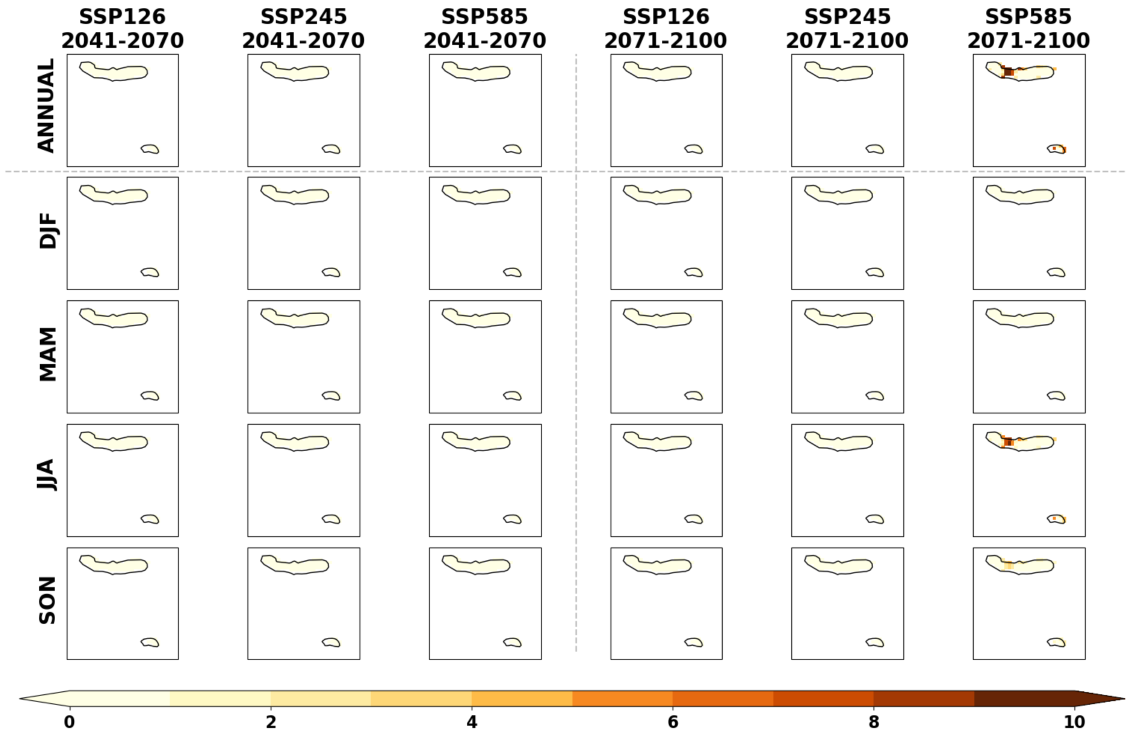

Figure 54 - Future projected changes in the number of hot days in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

The number of tropical nights in the 2041-2070 period (figure 56), show small positive anomalies in the SSP126 and SSP245 scenario, in the SSP585 projection the number of tropical nights increases on the northern coastal region of São Miguel Island (30-40 days/year) and similar increase can be found in Santa Maria. In the end of the century, no relevant increase is found in the best-case emission scenario, in the moderate emission scenario positive anomalies (30-40 days/year) are found along the north coast and in Pico da Pedra region in São Miguel, the same increase of the number of tropical nights can be found in Santa Maria. In the worst-case scenario emission scenario strong positive anomalies can be found in the coastal regions of São Miguel with values reaching 70-90 days/year, in Santa Maria the same high increase of the number of tropical nights is found. Seasonally, most of the increases comes from the summer and autumn months with a bigger contribution coming from the summer months.

In the region the number of frost days (figure 57) shows very little variations in all scenarios and study periods, with only a minor decrease (-2 days/year) near Furnas region in São Miguel Island.

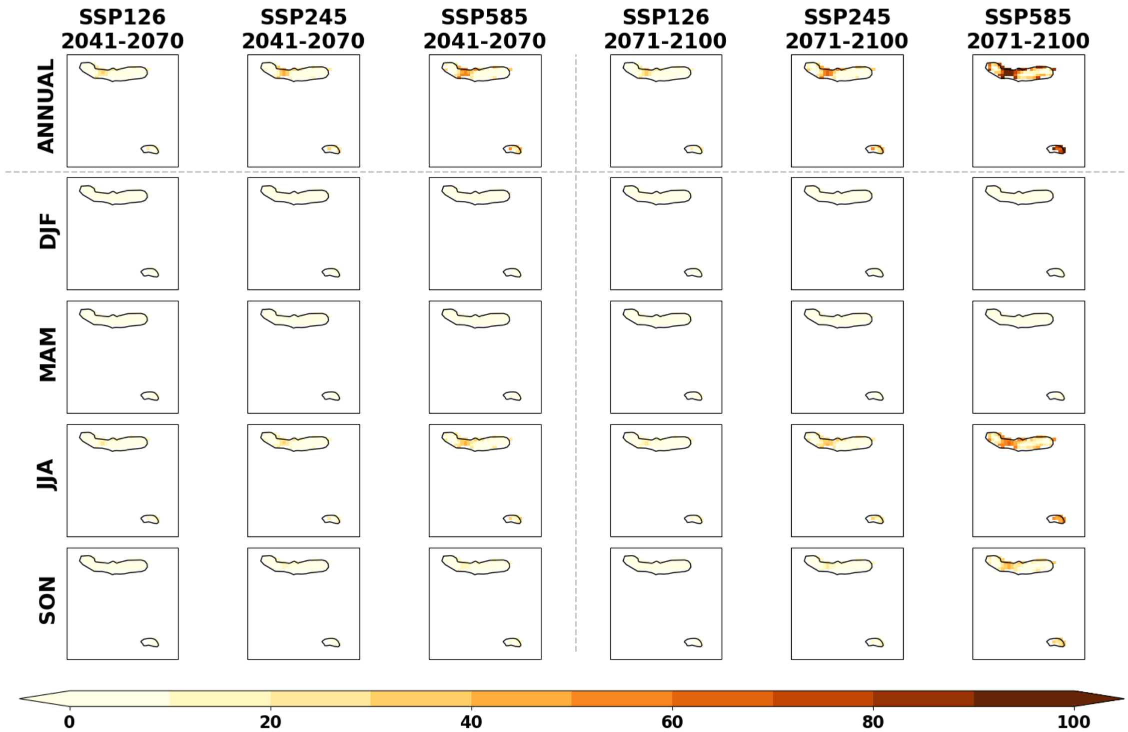

Figure 55 - Future projected changes in the number of summer days in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

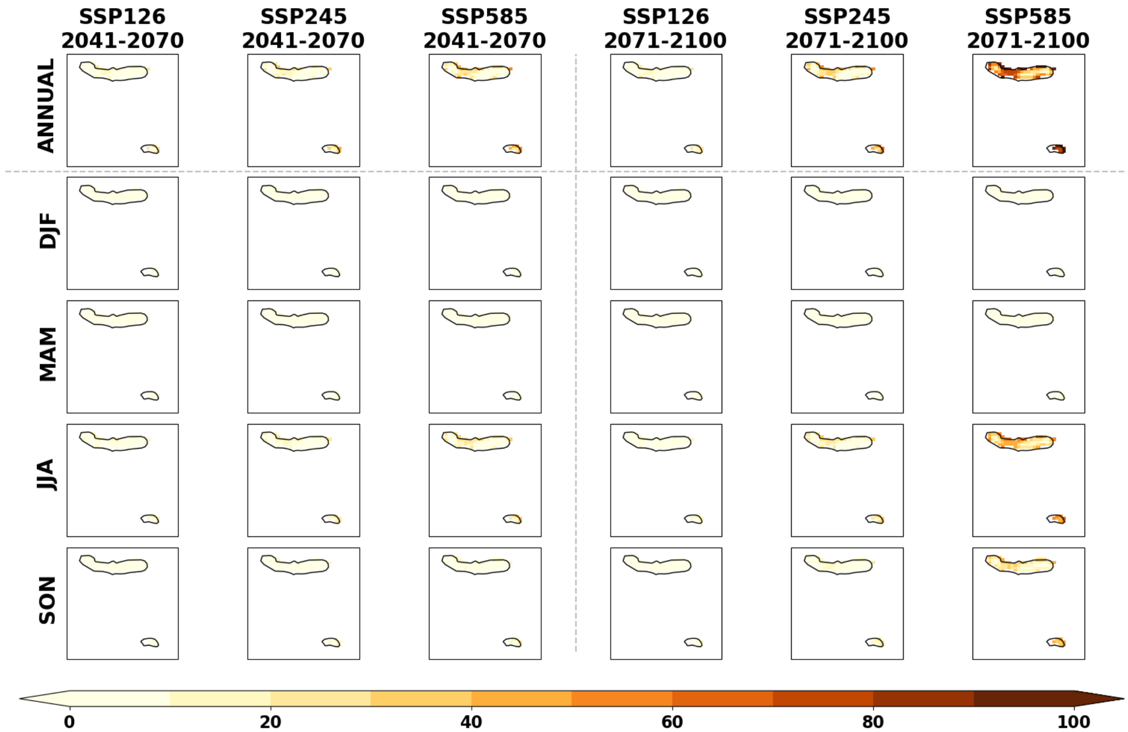

Figure 56 - Future projected changes in the number of tropical nights in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

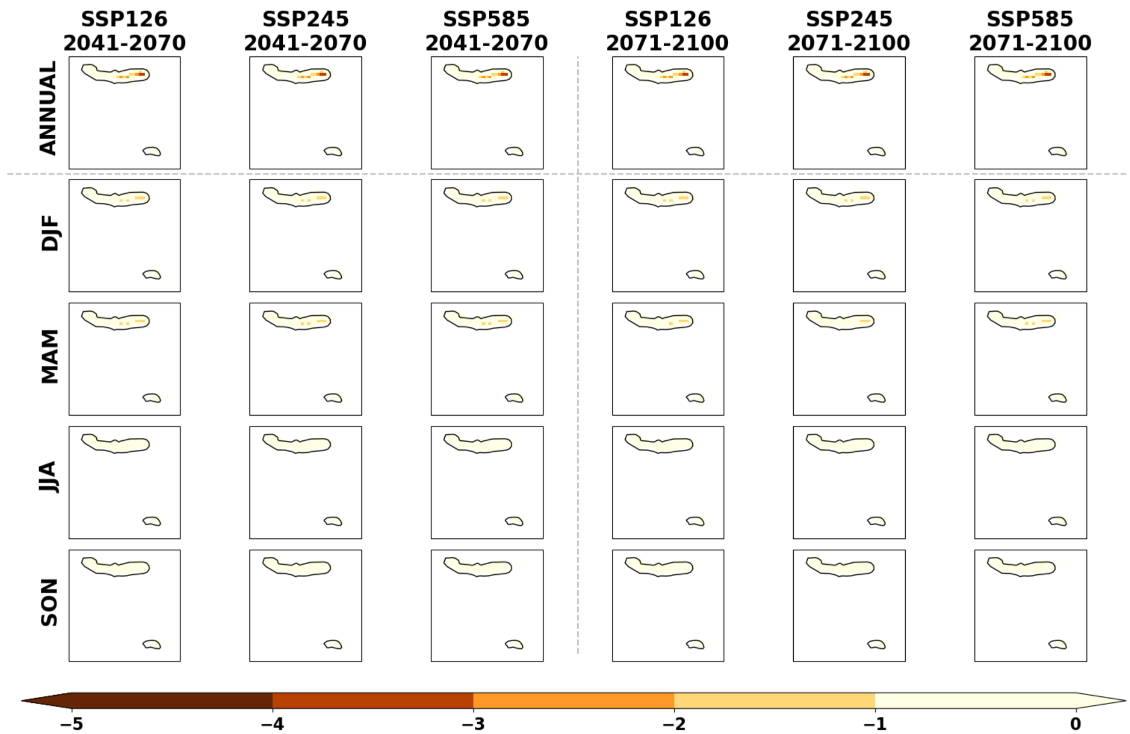

Figure 57 - Future projected changes in the number of frost days in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

6.2.1.3. Eastern Group

In the eastern group of the Azores archipelago the projected changes in the daily thermal range (figure 58) in all scenarios and time periods here shows little change with anomalies lesser than -0.2°C. The number of days in a heatwave (figure 59) shows similar patterns under SSP126 and SSP245 scenarios with positive anomalies ranging from 10 days/year in the southwestern part of Flores to 20 days/near in the north-eastern part of Flores. Same type of gradient is present under the SSP585 scenario but the increase of the number of days ranges from 20 days/year in the mid-century to 40 days/year. Seasonally, all positive anomalies occur mostly during summer with a minor anomaly in Autumn, with no changes during winter and spring.

The projections shows that the number of days in a coldwave (figure 60) shows a small anomaly in the SSP126 scenario in both periods. Under the SSP245 scenario in the mid-century anomalies are around 1 day/year and in the end of the century increases to 6 days/year. In the business-as-usual scenario in both periods negatives anomalies near -6 days/year can be found. Off course, most of these changes occur during the winter and spring months with no changes found in the remaining seasons.

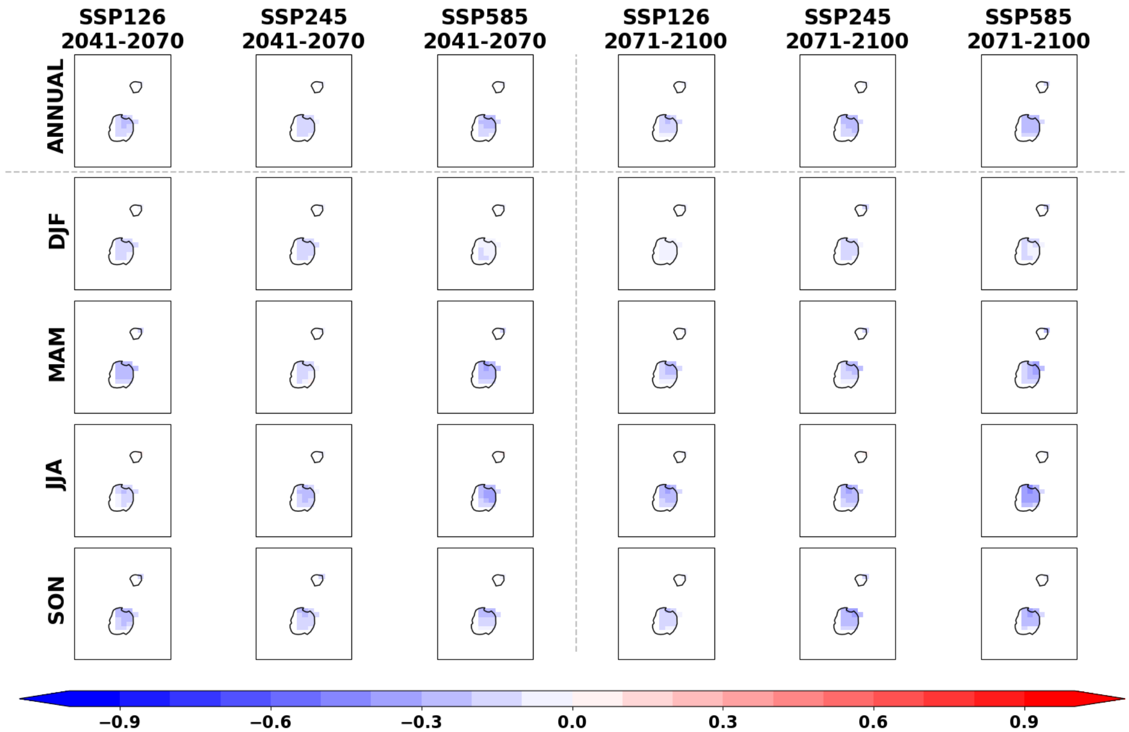

Figure 58 - Future projected changes in the daily thermal range in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

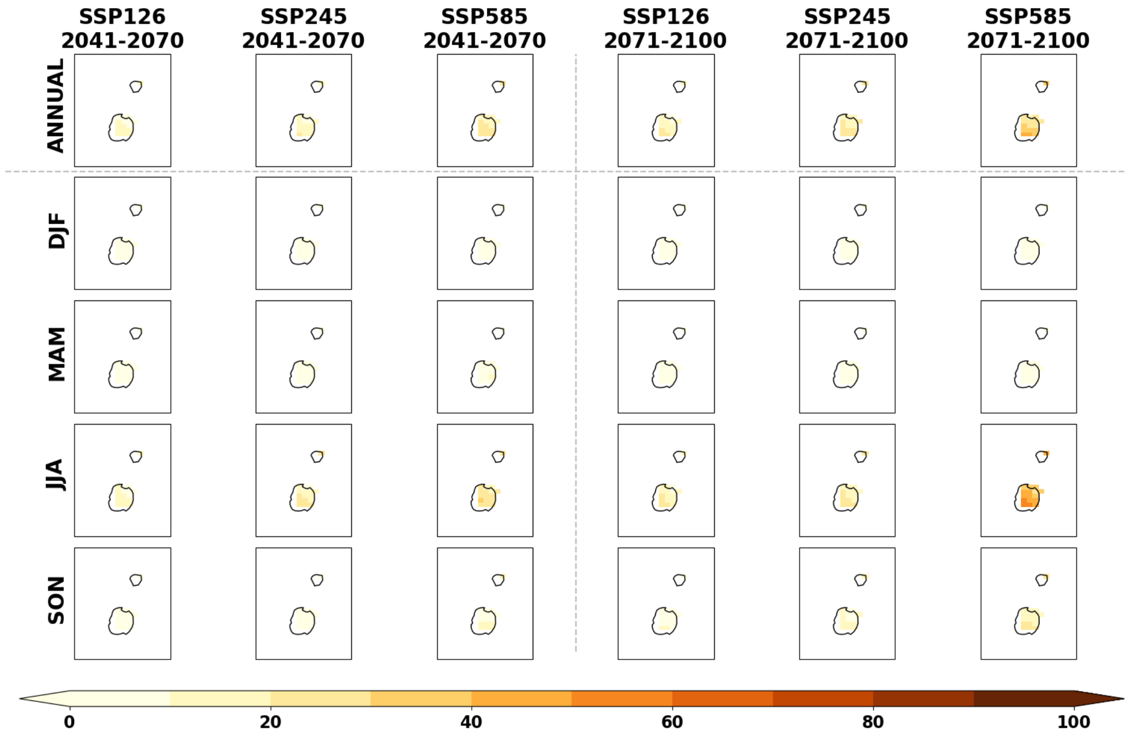

Figure 59 - Future projected changes in the number of days in a heatwave in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

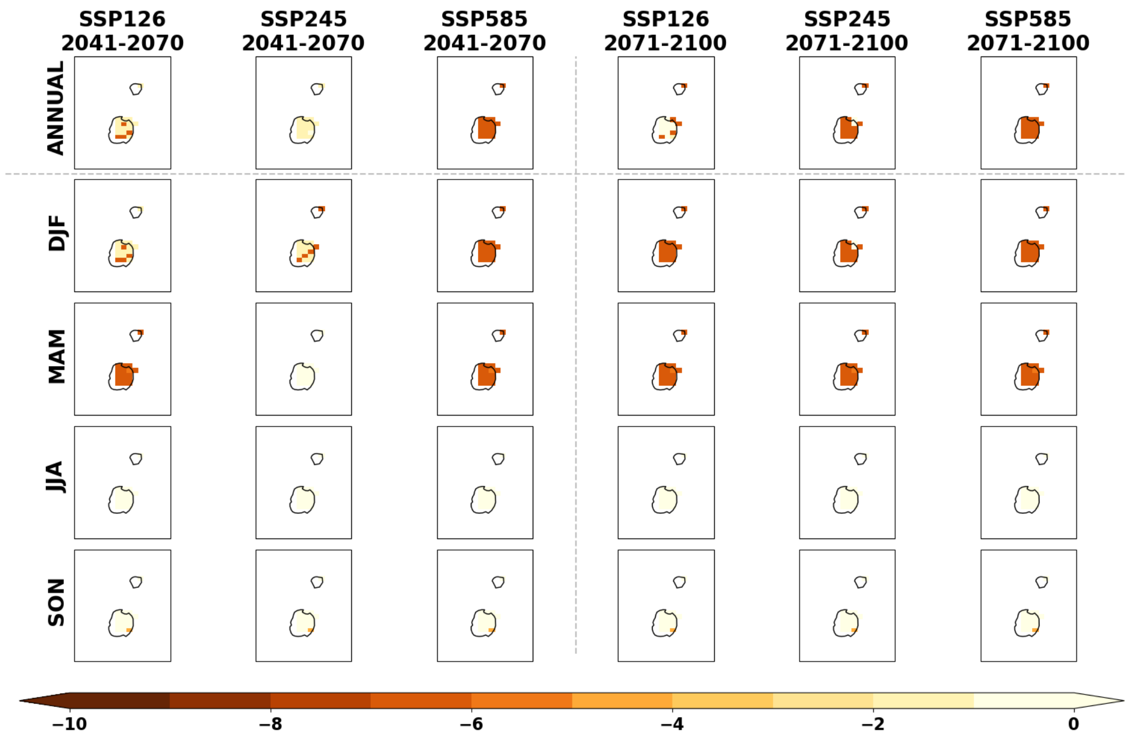

Figure 60 - Future projected changes in the number of days in a coldwave in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

Looking at the extremes, the number of hot days (figure 61) shows no variation and looking at the number of hot days only one grid point in Flores Island show a positive anomaly under the SSP585 scenario by the end of the century.

The number of summer days (figure 62) shows no relevant changes under the SSP126 scenario in both time periods. In the moderate emission scenario, we can find increases of 30 days/year in a small region in Flores Island in the mid-century, the region with 30 days/year increases in the end of the century in Flores and Corvo Island also shows the same anomaly value. In the business-as-usual scenario by the end of the century Corvo shows a positive anomaly of around 70 days/year and in Flores increases range from 30 to 80 days/year. Seasonally most changes are of course concentrated in the summer months, with minor changes occurring during autumn.

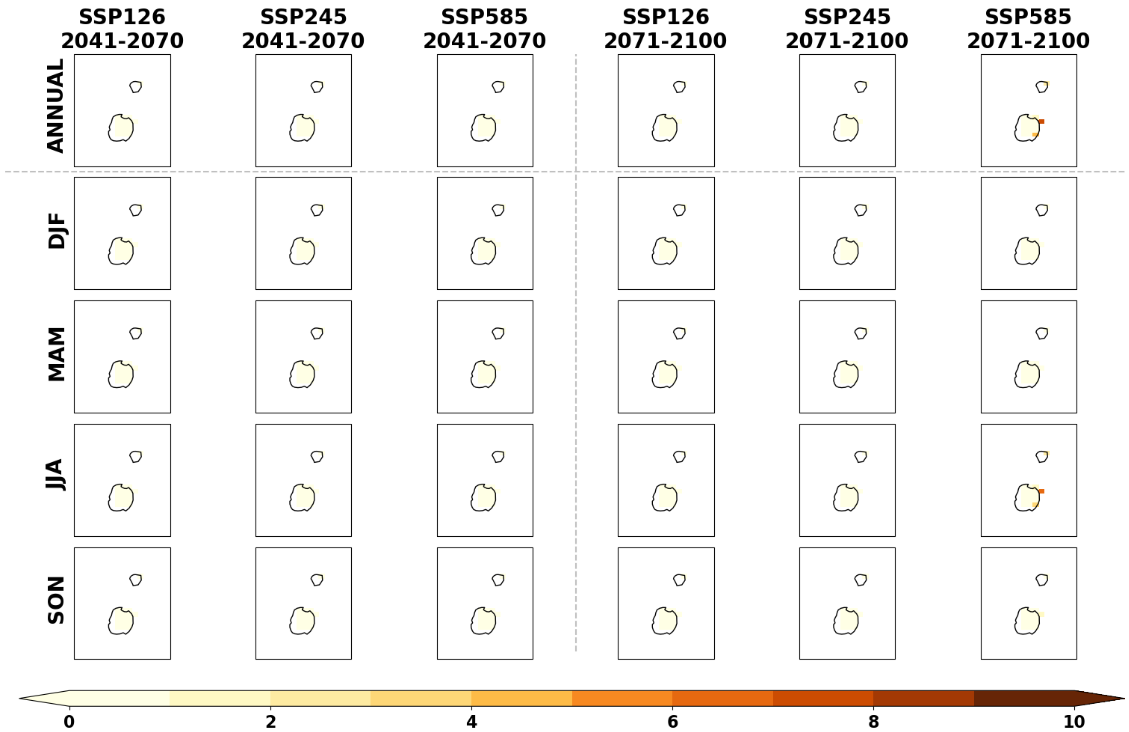

Figure 61 - Future projected changes in the number of hot days in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

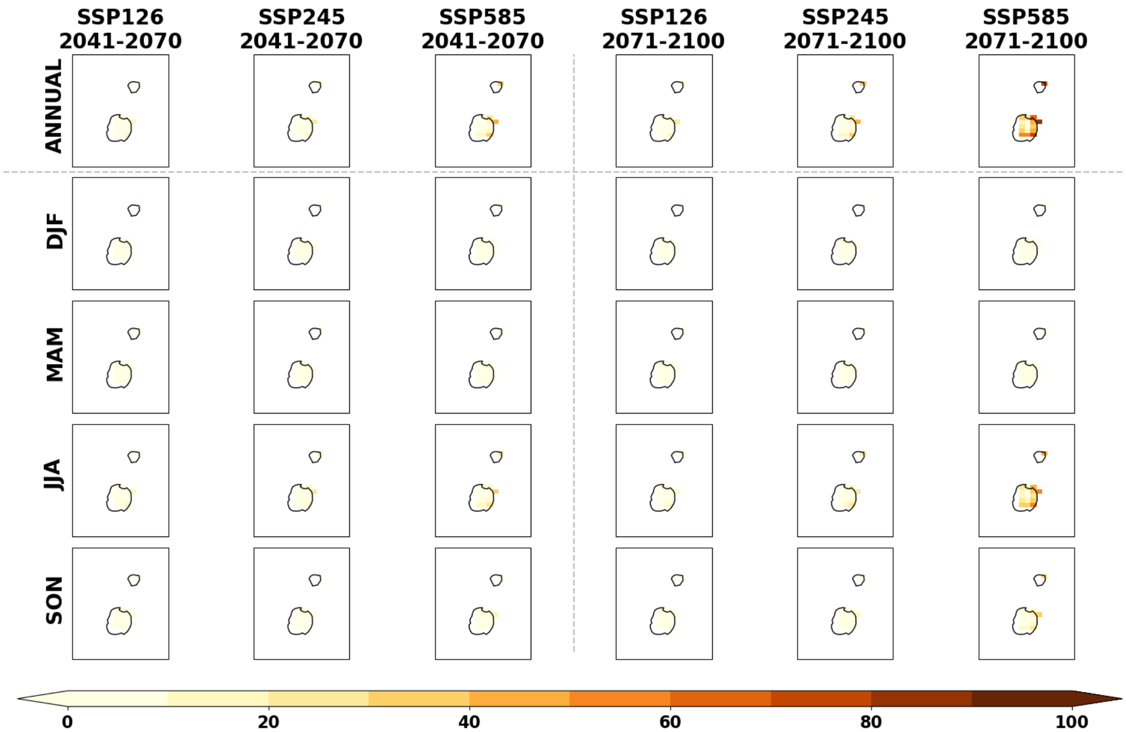

Figure 62 - Future projected changes in the number of summer days in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

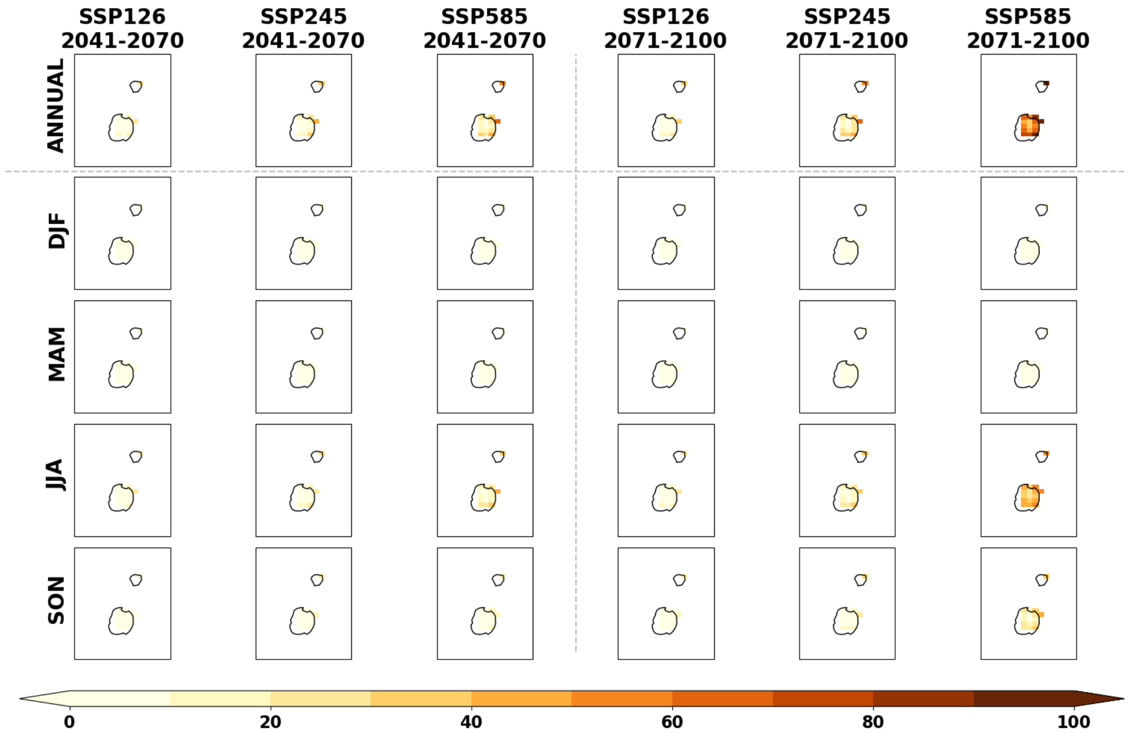

Figure 63 - Future projected changes in the number of tropical nights in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

The number of tropical nights under the SSP126 in both periods shows positive anomalies ranging from 20-40 days/year in Flores and around 30 days/year in Corvo (figure 63). Same patterns are found in both time periods in the SSP245 scenario with values higher than those found in the low-emission scenarios. Under the business-as-usual scenario by mid-century the number of tropical nights show increases between 25-45 days/year, and in the 2071-2100 the values vary between 40 to 100 days/year in Flores and Corvo shows an increase of 100 days/year. Seasonally these changes occur mostly during summer with a smaller contribute of the autumn months.

The projections show a similar pattern in all scenarios and in both time periods in the number of frost days (figure 64) with negative anomalies in Flores highest regions with all the remaining island showing no anomalies. Seasonally all changes occur during winter and spring with the largest occurring during winter.

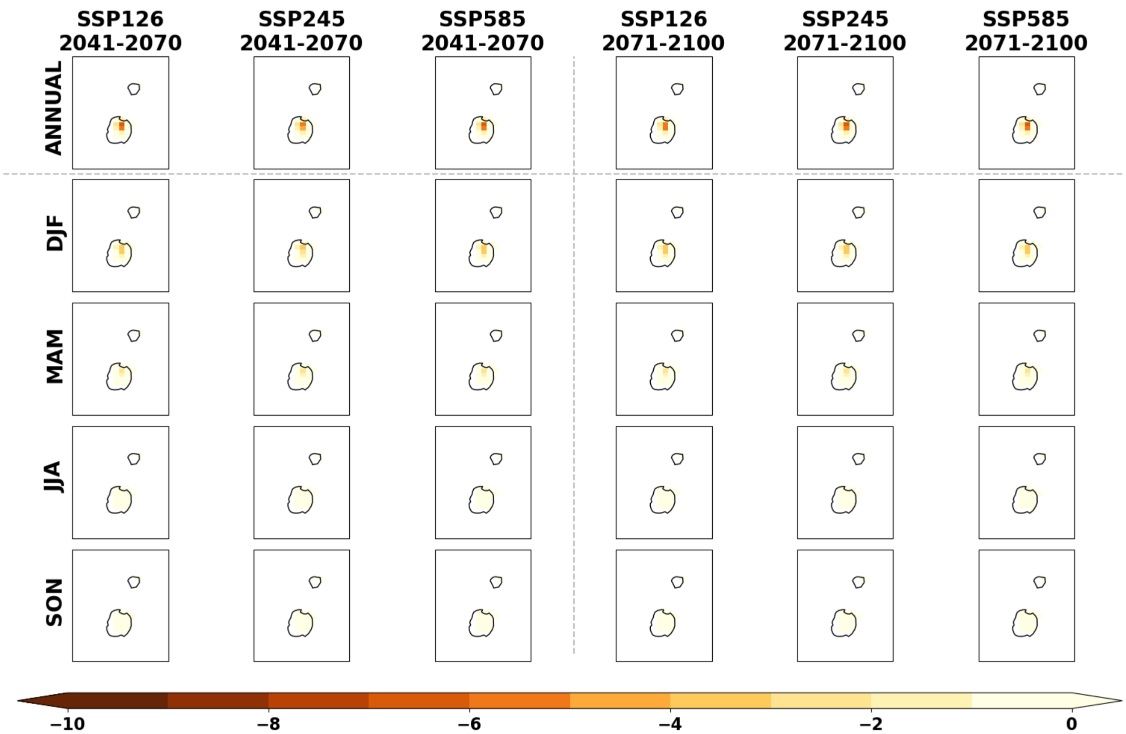

Figure 64 - Future projected changes in the number of frost days in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

6.2.2. Precipitation Extremes

6.2.2.1. Central Group

For the mid-century, the precipitation accumulated over a five-day period (figure 65) shows in the best-case scenario almost no changes, but over the Praia da Vitória in Terceira Island we find strong positive anomaly of 200mm.

In the moderate emission scenario, two positive anomalies of 200-250mm can be found in Terceira and Pico Island. For the business-as-usual emission scenario no relevant changes can be found in Faial and Graciosa Islands, In Pico Island in the mountains a negative anomaly can be located, and all the remaining island shows positive anomalies.In Terceira and São Jorge positive anomalies can be found all throughout the islands with values reaching 300mm. In the end of the century, in both SSP126 and SSP245 negative anomalies are found in the Pico Mountains, and in SSP585 positive anomalies are found in Praia da Vitória in Terceira Islands. Seasonally, most changes come from the winter (positive anomalies) and spring months (negative anomalies).

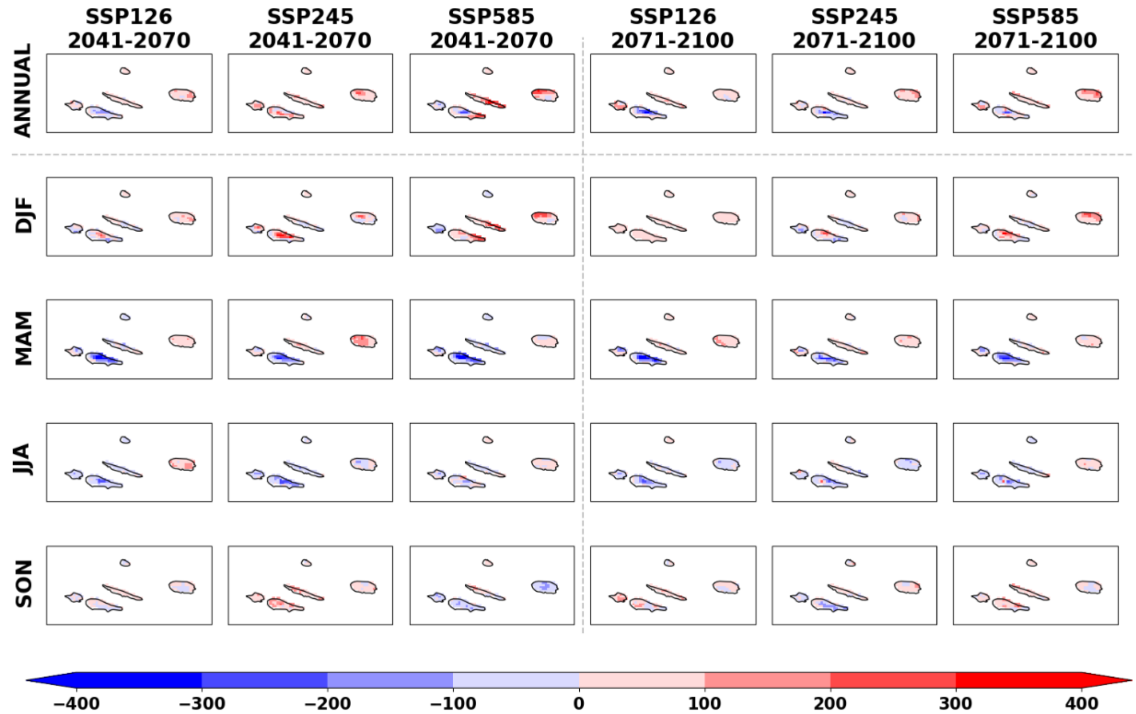

Figure 65 - Future projected changes in the maximum cumulative precipitation over a 5-day period in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

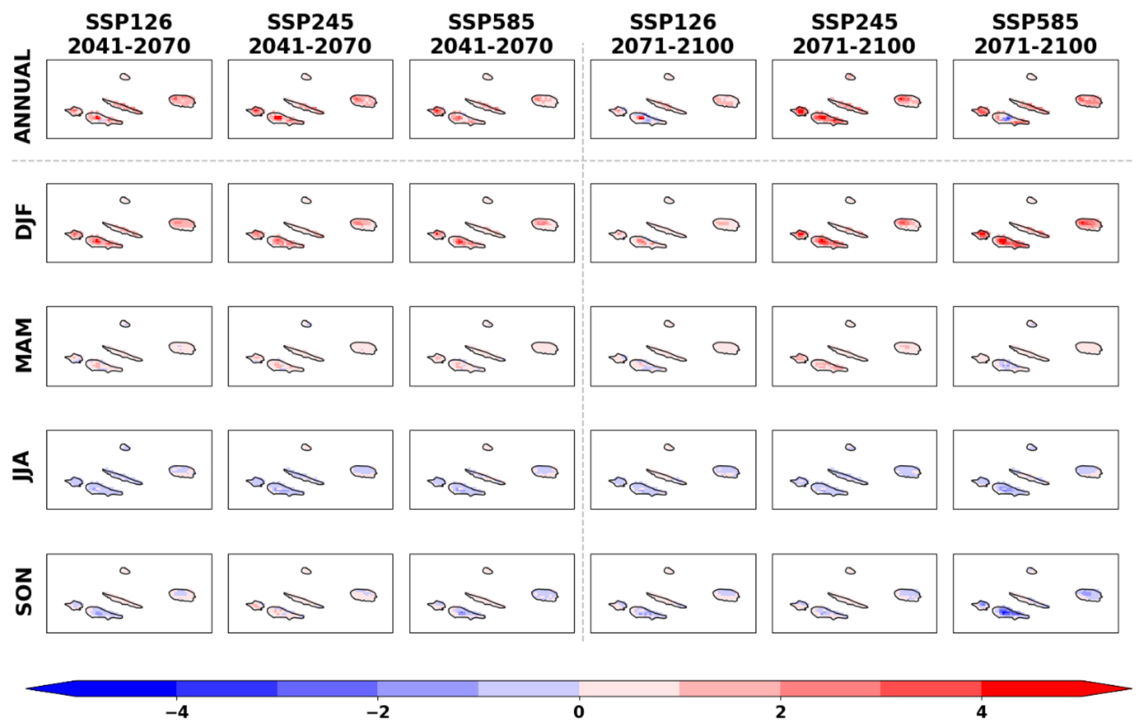

Figure 66 - Future projected changes in the number of days with precipitation exceeding 50 mm in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

The number of heavy rain days (figure 66), in both periods and in all scenarios, shows a small overall increase in all the islands in the central group with values not exceeding 3 days/year. Almost all these changes occur during the winter months, where all the islands have values of 3 days/year. In spring we also find minor positive anomalies, but the increases found here are counterbalanced by the negative anomalies occurring during the autumn months. Looking at the moderate-to-heavy precipitation days (figure 67), in the mid-century small positive anomalies can be found in all scenarios (4 days/year). In all scenarios however in the Pico Mountains we find negative anomalies (-2 days/year). In the end of the century again in SSP126 and SSP245 we have small positive anomalies, but in the SSP585 negative anomalies of 4-5 days/year are found in Pico Island and the north coast of Faial and Terceira Islands. Seasonally most positive anomalies come from the winter months, and the negative anomalies can be found in the autumn.

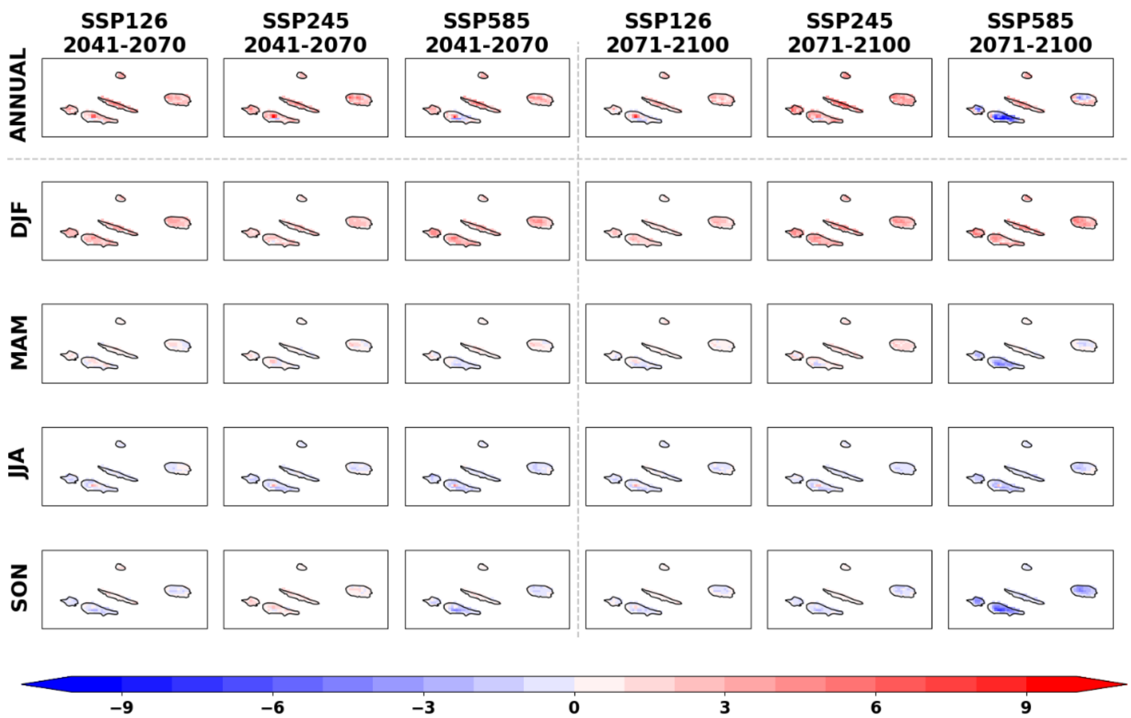

Figure 67 - Future projected changes in the number of days with precipitation exceeding 20 mm in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

The number of days with precipitation (figure 68), in the 2041-2070 period the SSP126 and SSP245 shows positive anomalies in all islands ranging from 5 to 10 days/year. In the SSP585 we still find the same positive anomalies, however in the southern coastal regions of Faial, Pico and Terceira a decrease of the number of precipitation days is expect.

By the end of century, the changes occurring in SSP126 are almost like the ones we find the 2041-2070 period, in the moderate emission scenario small gains in precipitation days are found but again negative anomalies are found along the southern coastal regions of Faial, Pico and Terceira Islands. In the business-as-usual scenario in the end of the century most of the islands show negative anomalies with values that can reach -15 days/year.

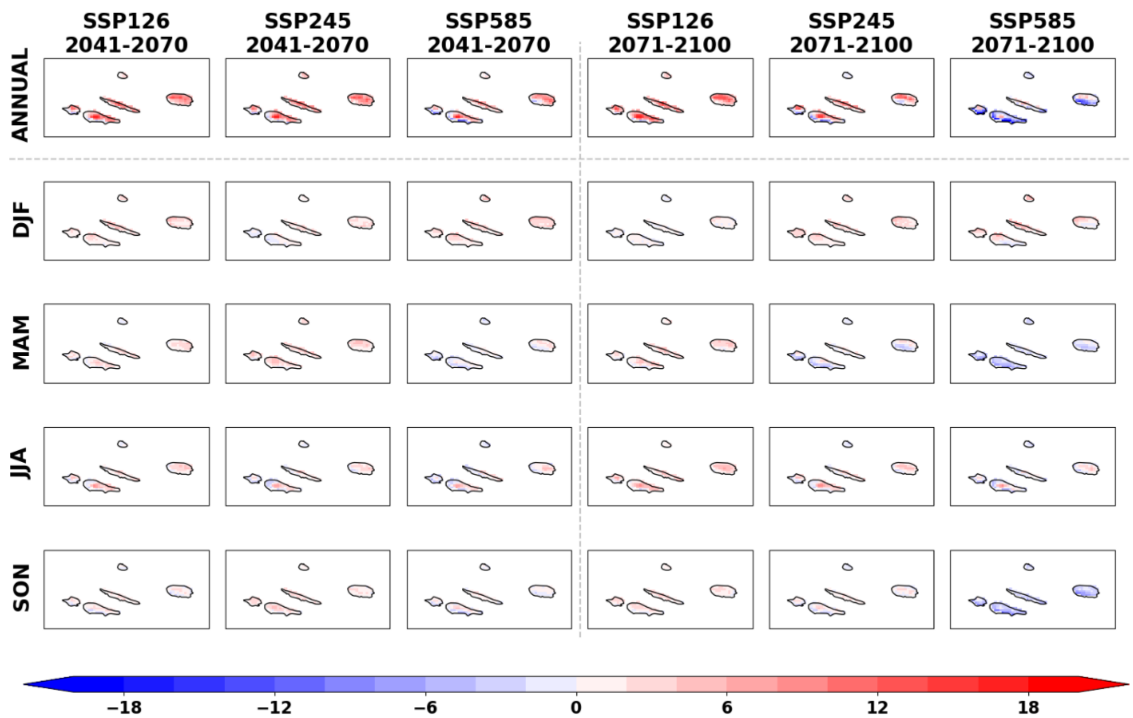

Figure 68 - Future projected changes in the number of days with precipitation exceeding 1 mm in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

6.2.2.2. Eastern Group

In the Eastern Group of the Azores Archipelago, the precipitation accumulated over a five-day period (figure 69), shows in the mid-century projections positive anomalies of around 100mm in the western region of São Miguel Island and negative anomalies in the remaining island (50-100mm) in all scenarios. In Santa Maria negative anomalies are found in the SSP126 and SSP585 scenarios (-100mm) and in the SSP245 we expect an increase of the precipitation accumulated over a five-day period (100mm). By the end of the century, in the best-case scenario most of São Miguel Island is under negative anomalies that can reach 200mm, in the SSP245 and SSP585 again we find that the western region of the island is expected to gain precipitation over a five-day period (near 200mm in the worst-case scenario) and the rest of the islands shows negative anomalies. Seasonally, in the 2041-2070 period all scenarios show increases of the precipitation over a five-day period in the winter, spring and summer months, during autumn São Miguel

Island shows negative anomalies. The same can be said for the 2071-2100, but with stronger negative anomalies during the autumn season.

The projected changes of heavy rain days (figure 70) in the 2041-2070 period shows small positive anomalies (2-3 days/year) in both islands, with the lowest anomalies found in the worst-case emission scenario. In the end of the century the anomalies found in all scenarios are almost equal to those we find in the 2041-2070 period. Seasonally, the increase of the number of days with heavy precipitation comes from the winter season, with all remaining seasons showing close to zero anomalies. The number of days with precipitation exceeding 20mm (figure 71) show similar results than the ones described for the heavy rain days, the only major difference occurs in the worst-case scenario during the 2071-2100 period, where projections show negative anomalies in the eastern part of São Miguel Islands. Seasonally this loss comes from the autumn and spring months, with the bigger contribution coming from autumn season.

The number of days with precipitation (figure 72) in the mid-century reveals an increase of 5 to 15 days in São Miguel for all scenarios, with the worst-case scenario having the lower anomalies. In Santa Maria the anomalies are lower than those found in São Miguel. In the 2071-2100 period same anomalies patterns can be found in the SSP126 and SSP245 scenario, but in the SSP585 scenario, Santa Maria is expected to have fewer precipitation days (10-15 days/year) and in São Miguel show a north-south split, in which the southern region losses precipitation days and the northern region gains precipitation days. Looking at the different seasons, in the mid-century projections all islands show positive anomalies in all seasons. The same can be said for the end of the century in the low and moderate emission scenario. In the business-as-usual scenario the losses of precipitation days described above mostly appear in the spring and autumn.

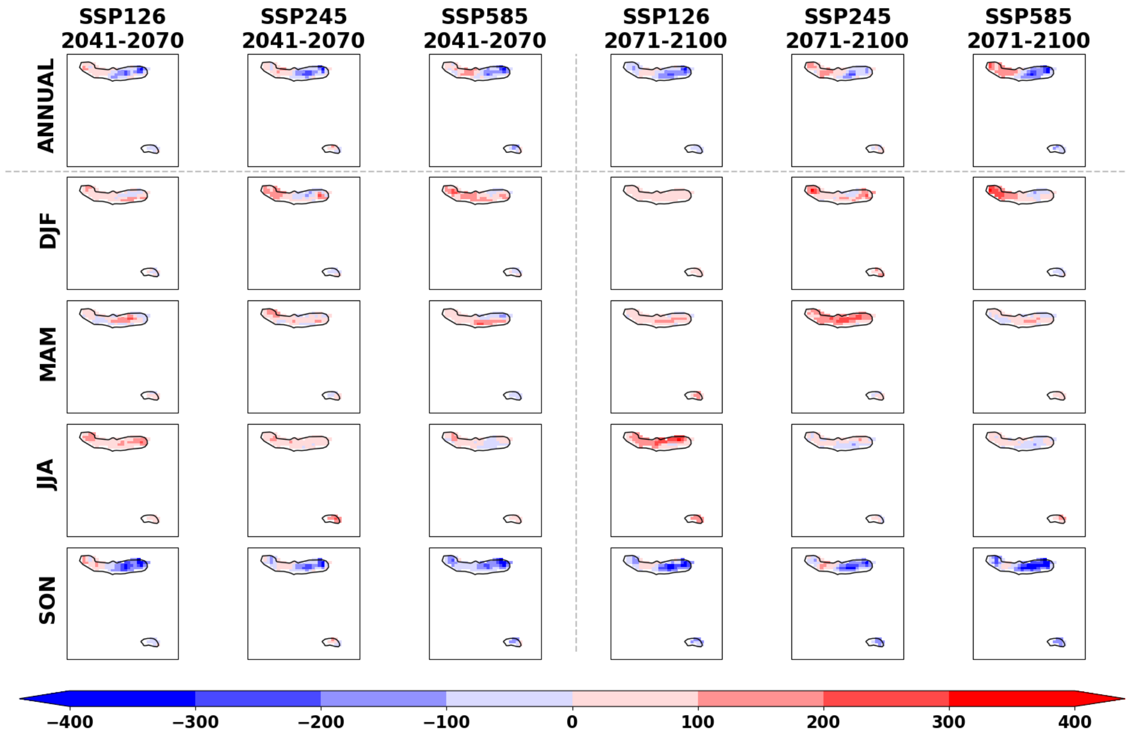

Figure 69 - Future projected changes in the maximum cumulative precipitation over a 5-day period in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

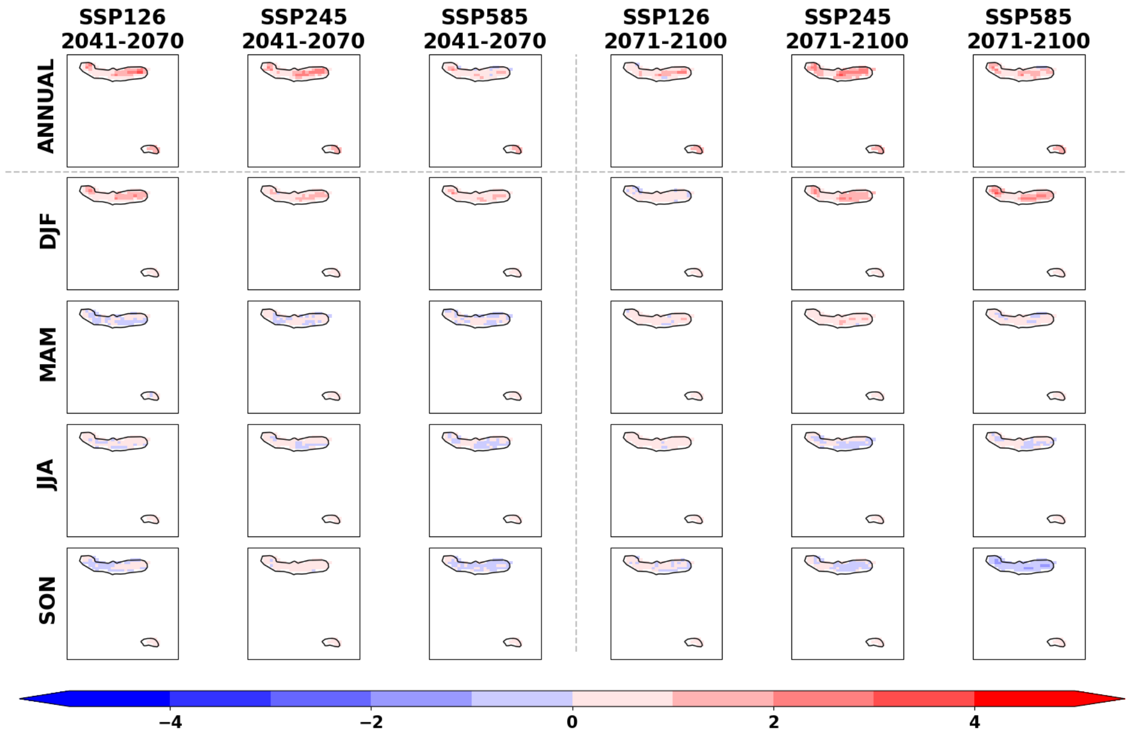

Figure 70 - Future projected changes in the number of days with precipitation exceeding 50 mm in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

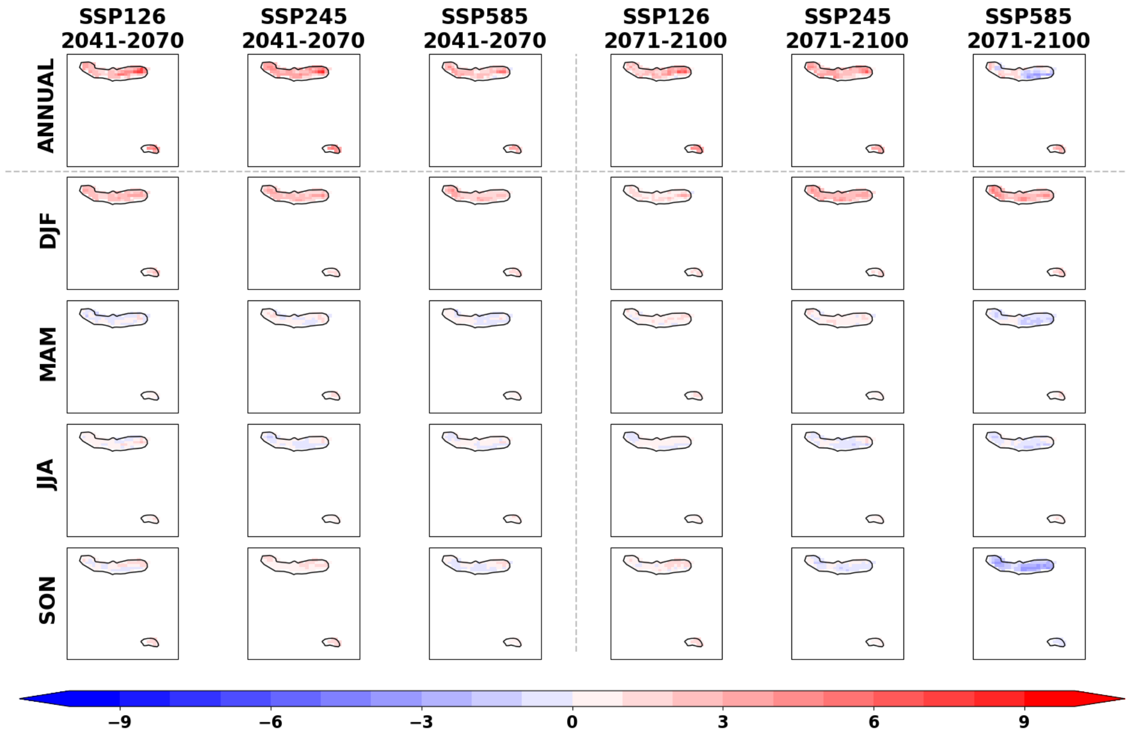

Figure 71 - Future projected changes in the number of days with precipitation exceeding 20 mm in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

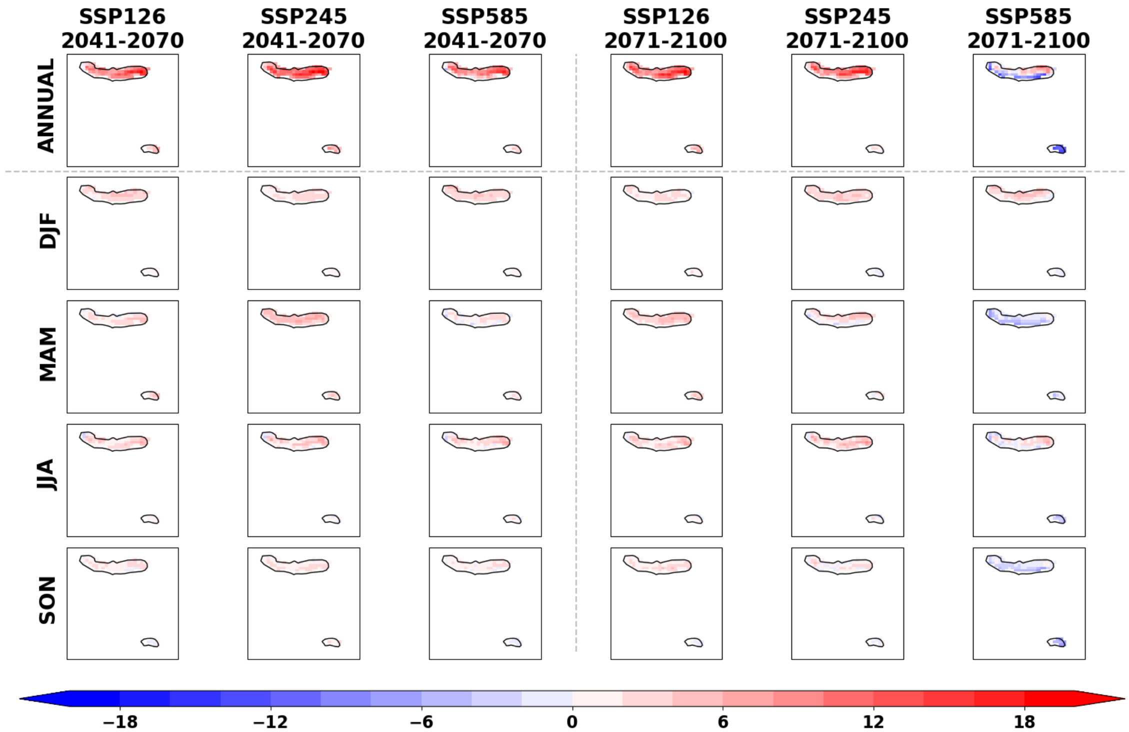

Figure 72 - Future projected changes in the number of days with precipitation exceeding 1 mm in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

6.2.2.3. Western Group

The precipitation accumulated over a five-day period (figure 73), in the mid-century shows little changes in the best-case scenario. In both SSP245 and SSP585 scenario we find positive anomalies of 50-100mm in the south coast of Flores Island and values above 150mm in the rest of the island. Corvo in the mid-century shows variations of around 100mm. In the endofthecentury SSP126 shows an increase of 150 mm cumulative precipitation in a 5-day period and changes between -50 to 50 mm in the rest of Flores Island. Under the moderate emission scenario positive anomalies are found in Flores Island with values varying between 100 to 300 mm. In the SSP585 scenario both islands show an increase of precipitation ranging from 50 to 150 mm. Seasonally, we notice both islands show negative anomalies during SON and gains occur during the other three seasons.

The future projected changes of the number of days with heavy rain (figure 74) shows an increase of events in both islands in all scenarios and time periods, ranging from 2 days/year under SSP245 in 2071-2100 and 6 days/year in the remaining cases. Heavy precipitation events show little to no change in the summer and autumn seasons and during winter and spring months anomalies are quite similar in the mid-century projections and in the end of the century anomalies are greater during winter. Projection changes in the number of days with precipitation greater than 20 mm (figure 75) shows similar anomalies patterns than the ones described in the heavy rain projection. Only noteworthy difference occurs in 2071-2100 period under the SSP585 scenario where a large part of Flores Island shows a decrease in the number of days with precipitation above 20 mm.

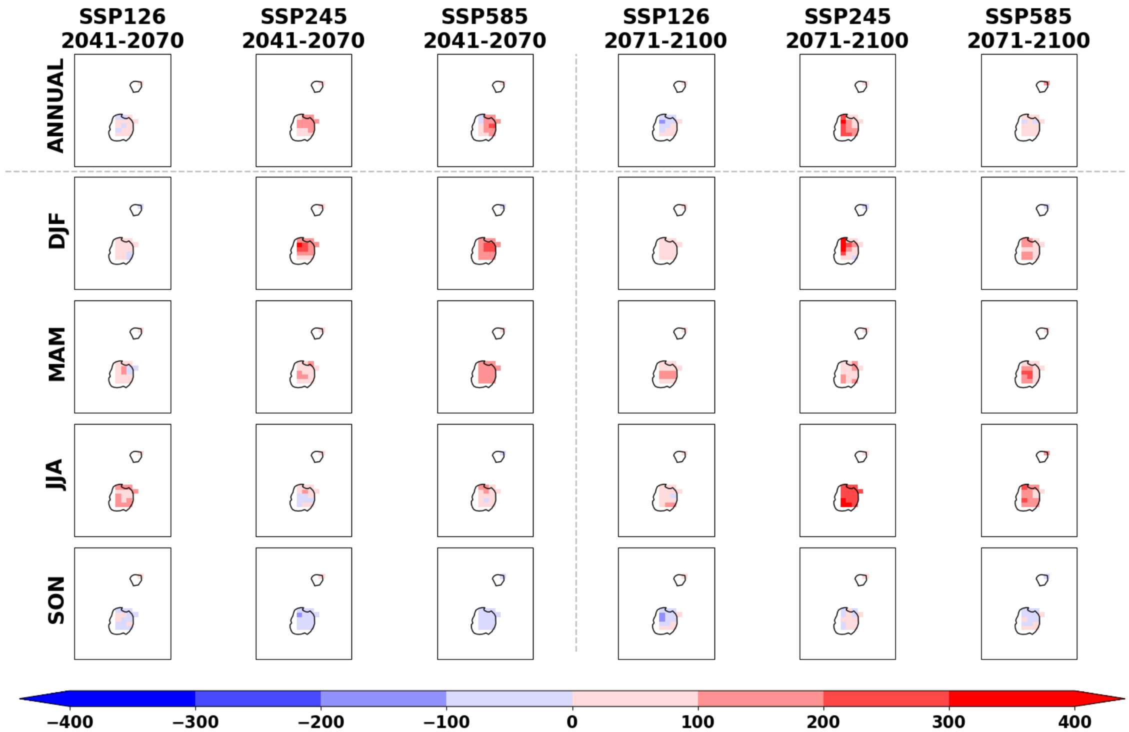

Figure 74 - Future projected changes in the maximum cumulative precipitation over a 5-day period in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

The number of days with precipitation (figure 76) in the mid-century reveals an increase in both islands in all scenarios (5-10 days/year).Along the south coast of Flores all projections show a decrease in the number of days with precipitation (-5 days/year). The pattern described can also be seen in both SSP126 and SSP245 scenarios in the later part of the century, but in the business-as-usual scenario projections point to a decrease of rainy days in the western group of islands in the Azores Archipelago. Most of future changes occur during the spring and summer months, with anomalies being close to zero during winter. In autumn only the relevant changes occur in the SSP585 scenario in both study periods projections pointing to a loss of precipitation days in both islands.

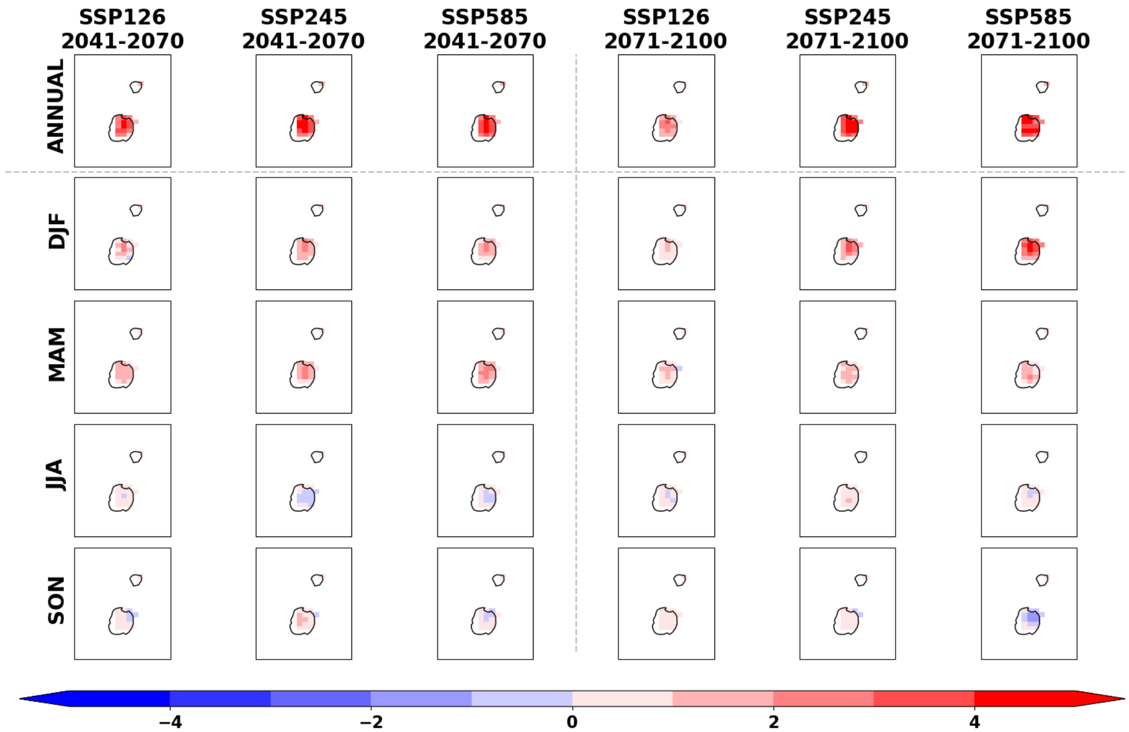

Figure 74 - Future projected changes in the number of days with precipitation exceeding 50 mm in the Azores Western Group(Units: days/year for the annual and days/season for the seasonal).

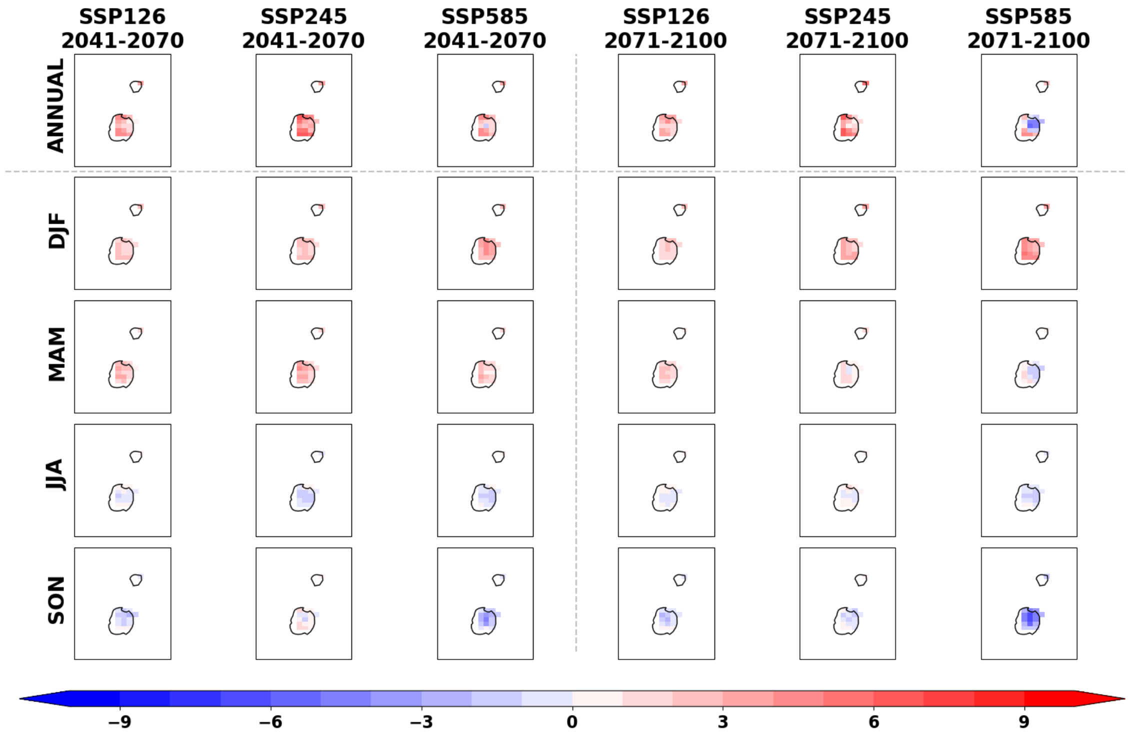

Figure 75 - Future projected changes in the number of days with precipitation exceeding 20 mm in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

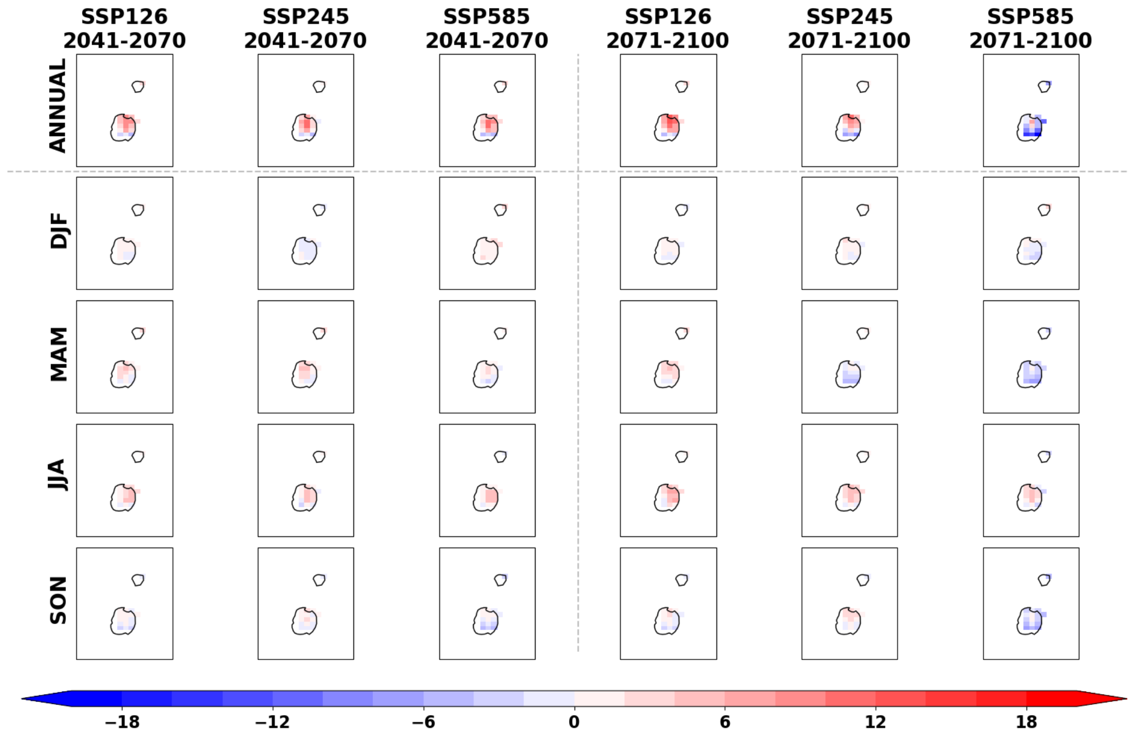

Figure 76 - Future projected changes in the number of days with precipitation exceeding 1 mm in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

6.2.3. Wind Extremes

6.2.3.1. Central Group

Looking at the annual anomalies of the number of days with 10-meter wind speed greater than 5.5m/s (figure 77), in the mid-century all islands show negative anomalies ranging from -5 to -15 days/year, with the anomalies being greater in the business-as-usual emission scenario. In the end of the century, the negative anomalies increase when compared with the 2041-2070 period and in the SSP585n scenario can reach values up to -30 days/year. Seasonally, is expected minor increases of days with 10-meter wind speed greater than 5.5m/s during the winter, and the remaining seasons projections showing negative anomalies, these anomalies are greater in the SSP585 in the 2071-2100 where in the autumn months can reach values of 15 days/year in all islands of the group. We could repeat what we just said for the number of days with wind greater than 10.5m/s (figure 78), but the anomalies in this case are lowest in comparison.

The number of days with wind lesser than 2.0m/s (figure 79), in the mid-century shows a small increase of the number of days (up to 10 days/year) in all scenarios. In the 2071-2100 period, the number of weak wind days increase slightly more in all scenarios when compared with the 2041-2070 period.

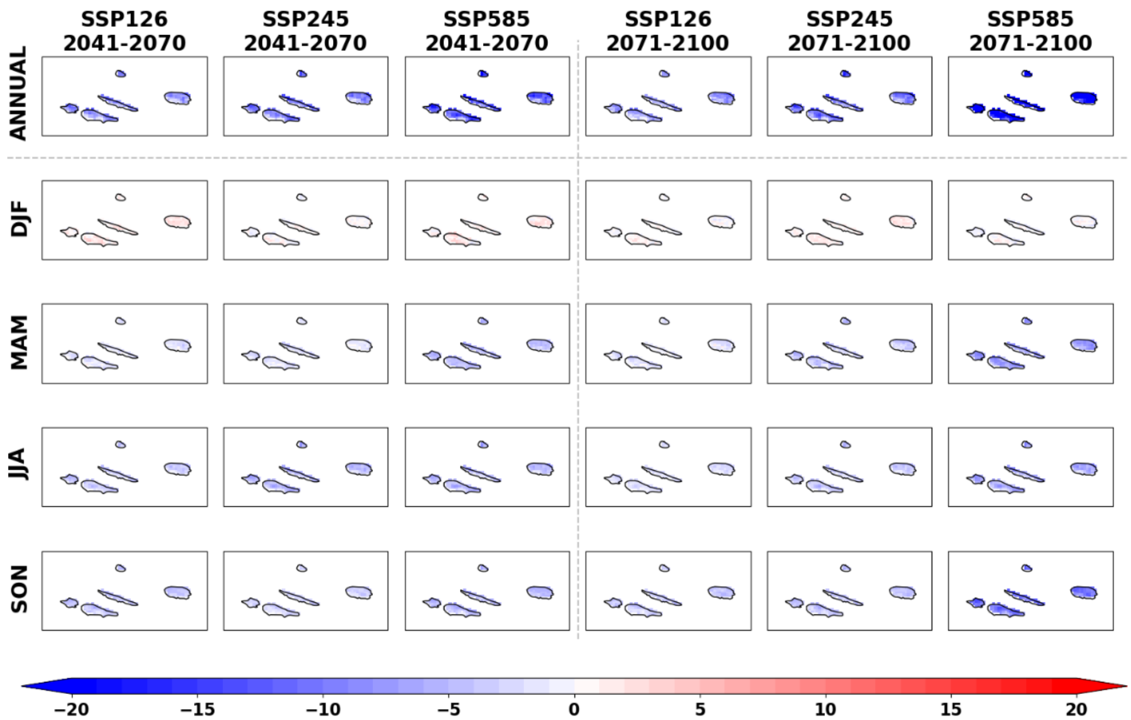

Figure 77 -Future projected changes in the number of days with 10-meter wind speed greater than 5.5 m/s in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

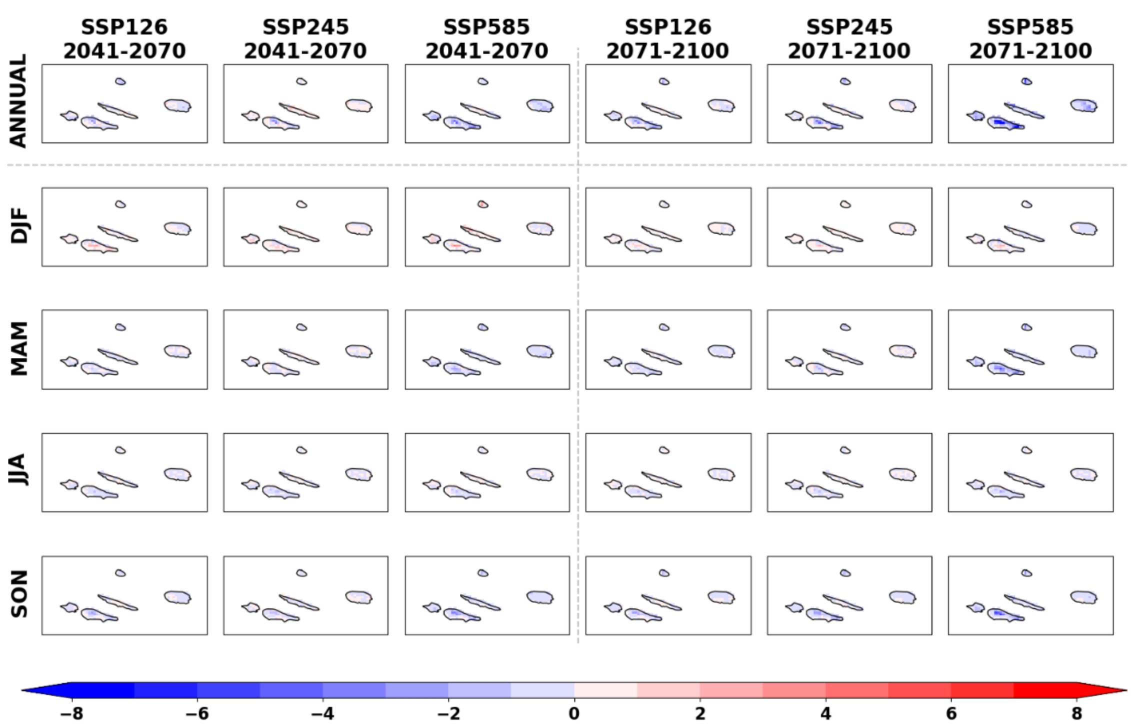

Figure 78 - Future projected changes in the number of days with 10-meter wind speed greater than 10.5 m/s in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

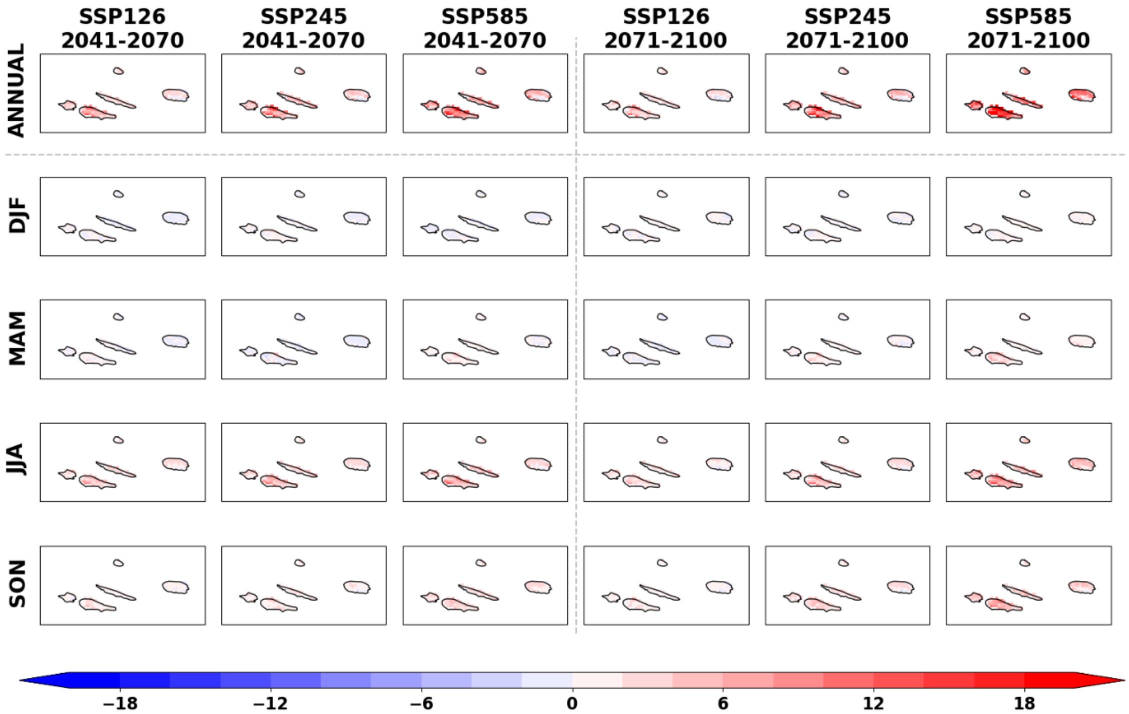

Figure 79 - Future projected changes in the number of days with 10-meter wind speed below 2.0 m/s in the Azores Central Group (Units: days/year for the annual and days/season for the seasonal).

6.2.3.2. Eastern Group

In the Eastern Group of the Azores Archipelago, the anomalies for the number of days with 10-meter wind speed greater than 5.5m/s (figure 80), in 2041-2070 show negative anomalies with the decrease ranging from -5 to -10 days/year in all scenarios with the largest anomalies in the worst-case emission scenario. In the 2071-2100 period we also find negative anomalies varying between -5 and -10 days/year in SSP126 and SSP245 scenario, and in the SSP585 scenario the anomalies are significantly higher with values reaching -25 days/year. In the winter season, all scenarios in both study periods have small positive anomalies (up to 5 days/year), the remaining seasons in the 2041-2070 project negative anomalies ranging from 1-5 days/year, the same anomalies can be found in the SSP126 and SSP245 scenarios in the 2071-2100 period. In the worst-case scenario in the 2071-2100, the anomalies are higher with values varying between 5-10 days/year.

The number of days with 10-meter wind above 10.5m/s (figure 81), show only marginal anomalies varying in all scenarios and study periods between -3 and 3 days/year, seasonally the gains in the number of days are mostly found in the winter, while the others seasons projections show small decreases in the number of days with 10-meter wind greater than 10.5m/s.

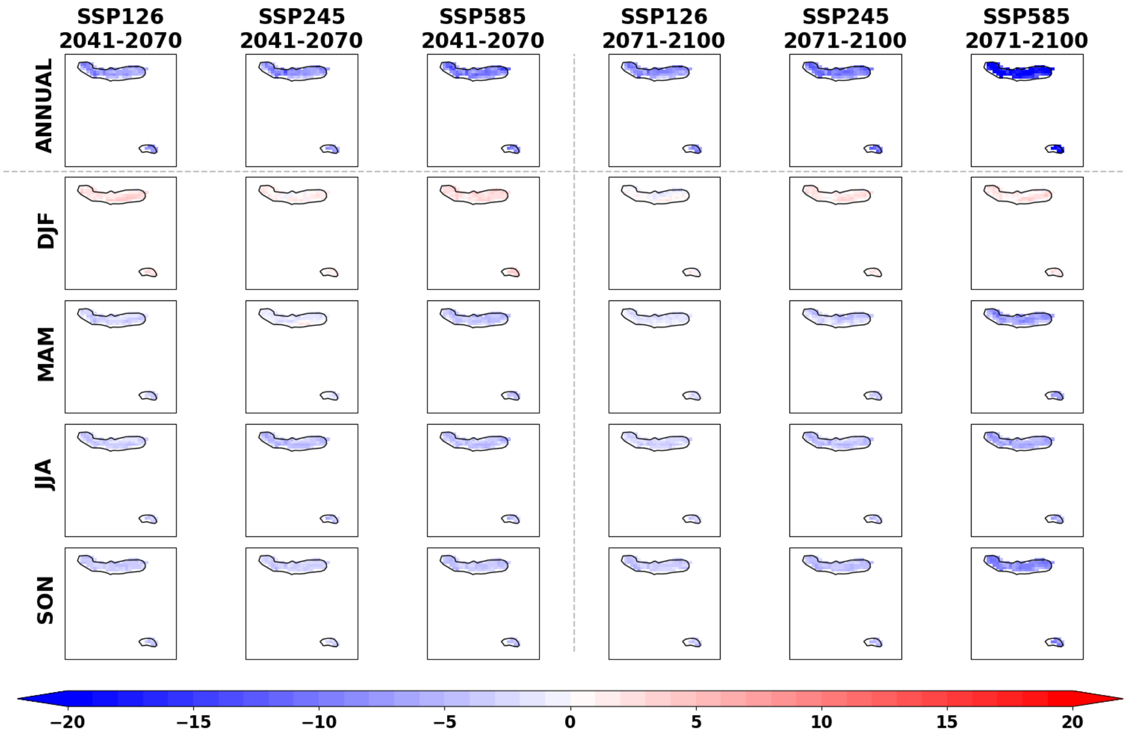

Figure 80 - Future projected changes in the number of days with 10-meter wind speed greater than 5.5 m/s in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

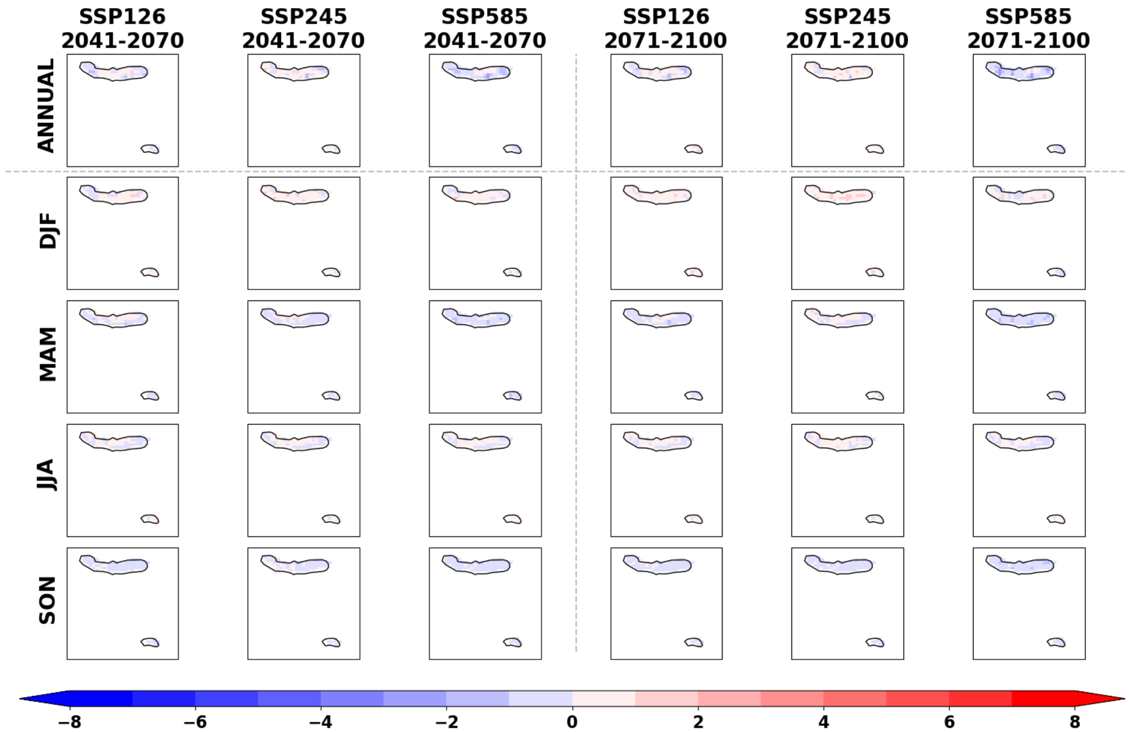

Figure 81 - Future projected changes in the number of days with 10-meter wind speed greater than 10.5 m/s in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

The number of days with 10-meter wind lesser than 2m/s (figure 82), shows small positive anomalies in both periods in the SSP126 scenario, in the SSP245 we expect a decrease in mild wind conditions ranging from 5 to 10 days/year in both periods. In the SSP585 scenario in the mid-century the increase of mild wind conditions can reach 12 days/year while in the later part of the century the increases can reach 20 days/year. Seasonally, most of the anomalies can be found in the summer and spring months.

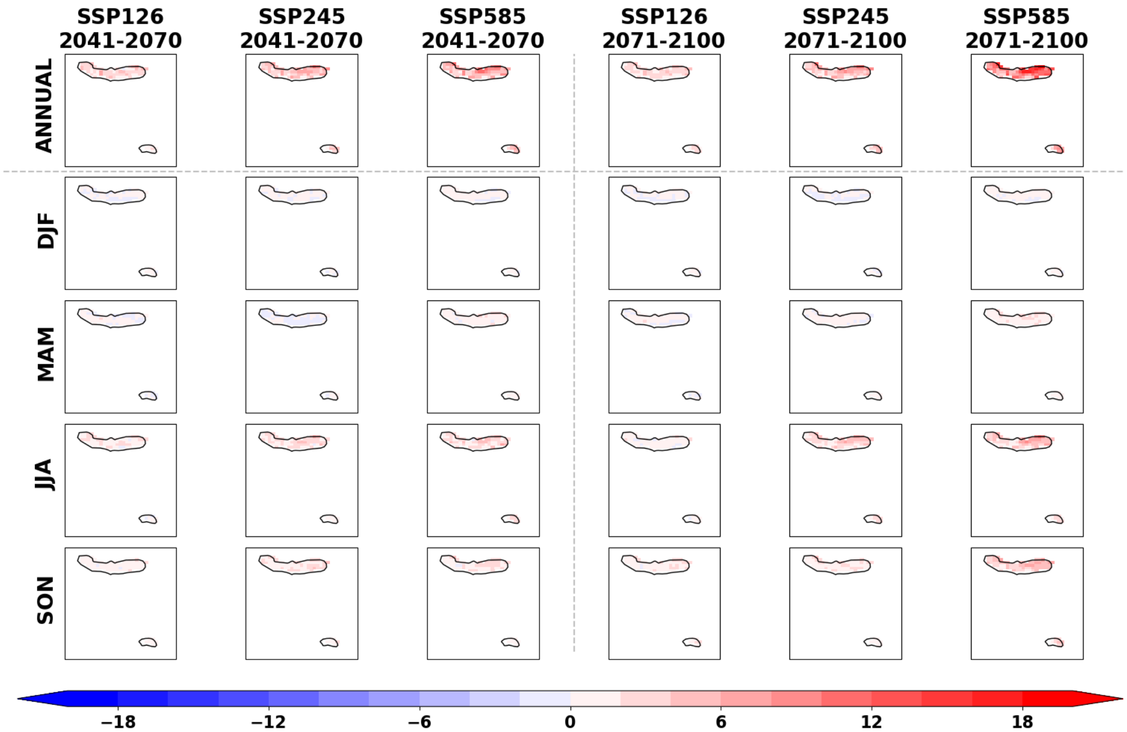

Figure 82 - Future projected changes in the number of days with 10-meter wind speed below 2.0 m/s in the Azores Eastern Group (Units: days/year for the annual and days/season for the seasonal).

6.2.3.3. Western Group

In the mid-century all scenarios, the number of days with 10-meter wind speed greater than 5.5m/s (figure 83), shows negative anomalies ranging between -10 days/year in the SSP126 scenario increasing to -15 days/year under SSP585. In the end of the century the anomalies increase in all scenarios with the business-as-usual scenario pointing to a loss of over 30 days/year. Seasonally the anomalies in the winter months are negligible and most of the year anomalies come from the summer and autumn months. Most of the same can be said about the number of days with 10-meter wind speed greater than 10.5m/s (figure 84), but the anomalies are smaller in comparison.

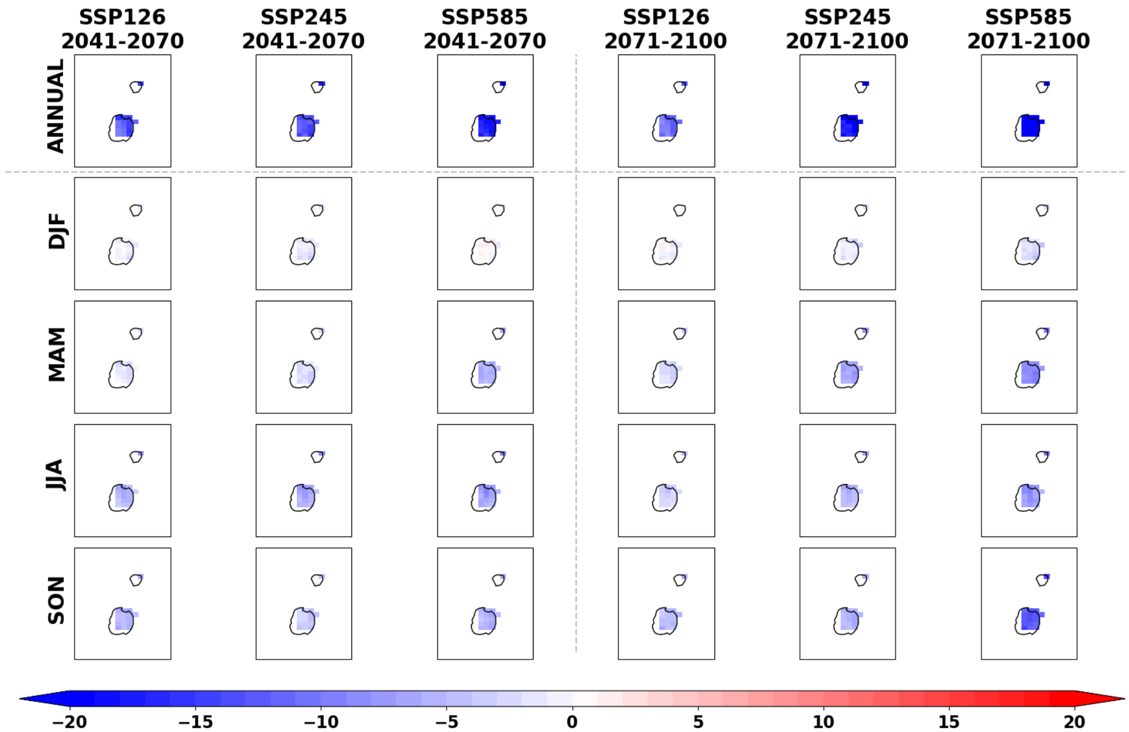

Figure 83 - Future projected changes in the number of days with 10-meter wind speed greater than 5.5 m/s in the Azores Western Group(Units: days/year for the annual and days/season for the seasonal).

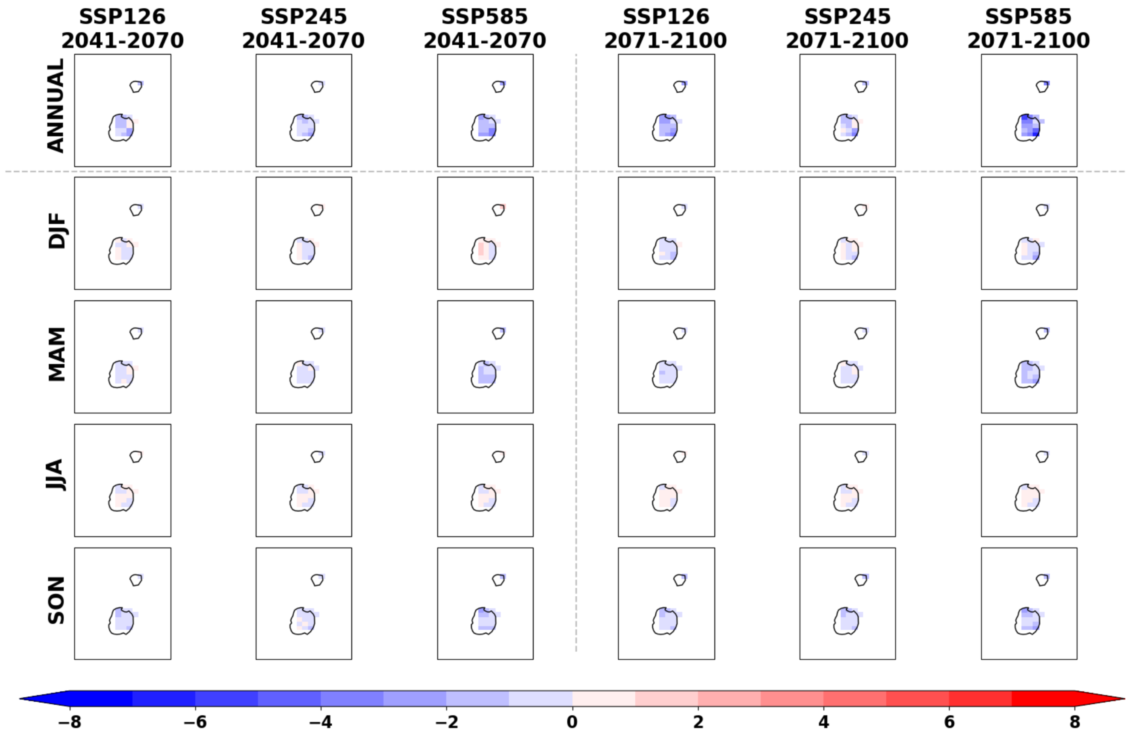

Figure 84 - Future projected changes in the number of days with 10-meter wind speed greater than 10.5 m/s in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

The number of days with 10-meter wind lesser than 2m/s (figure 85), show little change in both periods for the SSP126 scenario, in the SSP245 scenario the anomalies vary between 2 to 7 days/year in both time periods, with the largest increases found in the 2071-2100 period. The gain of mild wind condition days is largest in the SSP585 scenario, with values between 5 to 10 days/year in the mid-century, while in the end of the century projections show an increase of 10 to 20 days/year on mild wind conditions in the region. Most of the changes occur during the summer months with minor contributions during autumn.

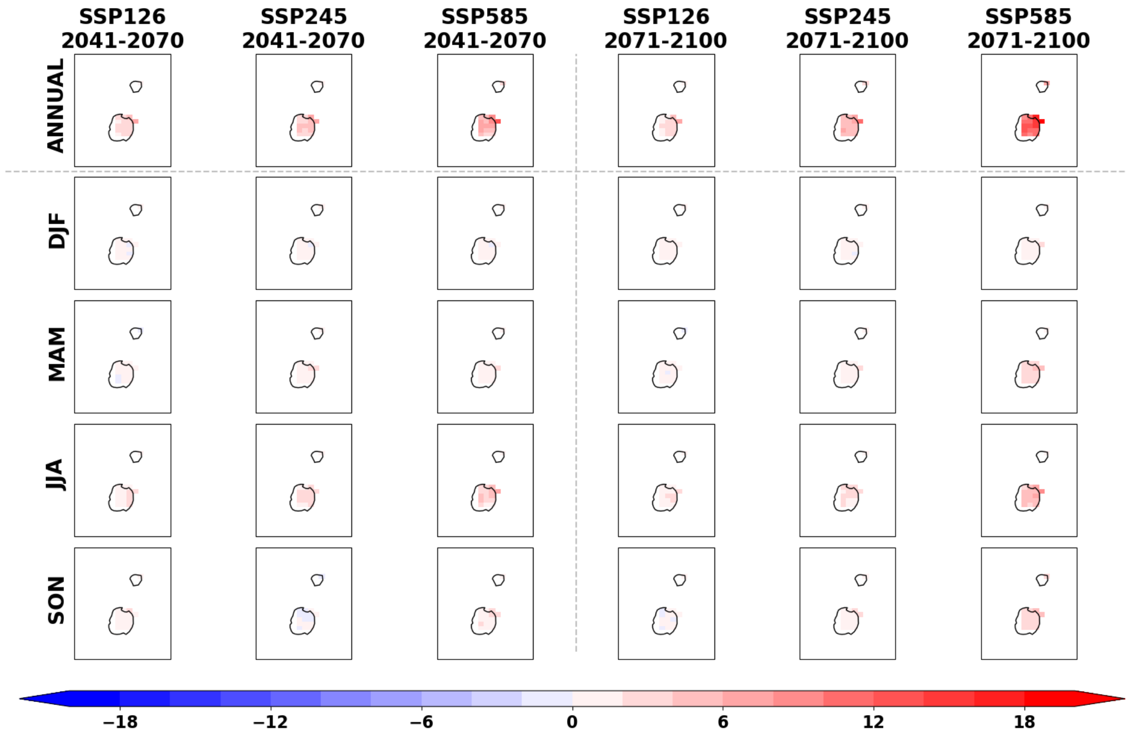

Figure 85 - Future projected changes in the number of days with 10-meter wind speed below than 2.0 m/s in the Azores Western Group (Units: days/year for the annual and days/season for the seasonal).

7. Conclusions

The error assessment in the Madeira and in the Azores Archipelago, shows that the downscaling model has a strong positive impact in the simulation of local precipitation. Overall, the WRF simulations show better correlations, lower error metrics and do a better job explaining the local variability than the global models. The metrics for the minimum and maximum temperature show that the reanalysis does well predicting these variables and the downscaling model forced by it is still able improve on those predictions. Comparing EC-Earth global model results against the WRF_{ec} simulation, the maximum air temperature metrics show a better performance of the downscaling model, with the WRF_{ec} simulation doing a good job explaining the local variability. In the minimum air temperature, the EC-Earth model has better metrics than the downscaling simulation (the downscaling over cools the regions) however the WRF simulations have better correlations and explain the local variability better.

Under the SSP126 scenario, the downscaling methodology used here, shows that in the mid-century both islands in the Madeira Archipelago are expected to have an increase of mean air temperature around 2.2°C. In this scenario the warming trend between the two future periods is small with the air temperature increase rising to 2.3°C in Madeira and 2.5°C in Porto Santo in the 2071-2100 period. In the moderate emission scenario, the warming trend increases, in the 2041-2070 an increase of temperature of 2.6°C is expect in both islands, with a further increase of 0.6°C by the century end. The business-as-usual scenario shows an increase of 3.0°C in both islands in the mid-century. By century end in this scenario one can expect an increase of air temperature of 4.9°C in Madeira and 4.6°C in Porto Santo.

In the mid-century the amount of precipitation in Madeira Archipelago has little changes, with minor decreases in the SSP585 scenario (2%), and minor gains in the remaining scenarios (2-5%). In the latter part of the century in the low emission scenario precipitation gains of over 10% are expected, the moderate emission scenario should have a small decrease in precipitation in both islands (below 5%), but in the business-as-usual scenario a precipitation loss of over 10% is expected in both islands.

For the wind resources available in the Archipelago, simulations shows only minor losses in all scenarios and periods. Overall, in the mid-century results show a loss of 2% in the three scenarios, and in the end of the century the expected losses are below 4%.However there is some evidence of increased wind near Madeira Airport, consistent with the findings of Miranda et al. (2021) for recent decadal trends.

In the Azores Archipelago the islands in the Western Group show smaller air temperature anomalies (0.2°C) when compared to the remaining islands in the Archipelago. In all three groups in the Archipelago, the air temperature trends within the islands that constitute each group are almost equal. In the mid-century the low emission scenario in the Western Group, an increase of air temperature of 2.2°C is expected. This increase rises to 2.4°C in the remaining islands. Under this scenario a further increase of around 0.1°C in all islands is predicted for the end of the century. The moderate emission scenario shows an increase of temperature in the mid-century of 2.5°C for the Western Group and 2.7°C in the remaining islands. For the century end a further increase of 0.5°C to 0.6°C is expect. In the 2071-2100 period under the worse emission scenario a temperature increase of 4.9°C is predicted for the Central and Eastern Group with the predictions pointing to a warning trend of 4.6°C in the Western Group. In the mid-century the warming trends in all islands are lower by around 1.5°C.

Looking at the precipitation anomalies, in both time periods on all the scenarios the model predict an increase of precipitation in all islands. In the lower emission scenario, in both time periods precipitation is expected to increase between 5 to 18% with the precipitation gains being smaller in the 2071-2100 period. The highest gains in precipitation occur under the SSP245 scenario again with the highest values found in the mid-century. For the business-as-usual scenario, the gains in precipitation in the region are smaller, the precipitation is expected to rise between 4 to 13% in the mid-century and between 3 to 10% in the 2071-2100 period.

Overall, the wind resource in the Azores Archipelago is expected decrease. The mid-century model predictions show a decrease of wind of 2 to 4% in the SSP126 and SSP245, and between 3 to 5% in the SSP585. The highest losses in wind speed can be found in the business-as-usual scenario, with losses ranging from 3 to 5% in the mid-century and between 6 to 9% in the end of the 21st century. In all scenarios the largest drop in wind speed can be found in the Eastern Group and the lowest in the Western Group.

In both Archipelagos one can expect an increase of the number of summer days and tropical nights. The increase is mostly located along the coastal regions of the islands, and the increase is particularly strong in the end of the century under the SSP585 scenario. Overall, in the Madeira Archipelago, we can expect less precipitation days but more frequent moderate to heavy and heavy precipitation days during the raining season. The number of precipitation days in the Azores Archipelago is expected to decrease under the SSP585 scenario in the 2071-2100 period, however in the remaining scenarios/periods under consideration the number of precipitation days should increase. Again, like in the Madeira case, the number of days with moderate to heavy and heavy precipitation days should increase.

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