Characterization and Future Projections of the Azores Anticyclone

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Abstract

This project deals with the characterisation and effect of the Azores anticyclone and its impact on the Canary Islands, analysing recent historical data (1980-2014) from the ERA database5 and future climate simulations (2065-2099) using CMIP6 climate models. The methodology used to characterise both the position of the anticyclone centre and the intensity of the anticyclone is described. The results show considerable fluctuation during winter, with many strong anticyclone events, as opposed to greater stability during summer.

The most remarkable results of the projections highlight a behaviour in spring and autumn that tends more towards summer, as well as a displacement of the anticyclone towards the east. The analyses, in which bootstrap techniques have been used for the three metrics, show slight differences, suggesting changes in the structure and behaviour of the anticyclone in the future. The results point to a scenario in which climate change is intensifying the occurrence of high-pressure days during the winter season, as well as weather stability in the summer months, which would result in warmer and drier conditions for the Canary Islands. The study has not only indicated the need to further examine the effects of the interaction of the Azores Anticyclone with other regional systems, but also to assess the implications for such crucial sectors as agriculture and tourism.

Resumen

Este trabajo de fin de grado trata la caracterización y el efecto del Anticiclón de las Azores, a la vez que su impacto en las Islas Canarias, analizando datos históricos recientes (1980-2014) a partir de la base de datos de ERA5 y simulaciones climáticas futuras (2065-2099) utilizando modelos climáticos de CMIP6. Se describe la metodología empleada para caracterizar tanto la posición del centro del anticiclón como la intensidad del mismo. Los resultados muestran una fluctuación considerable durante el invierno, con muchos eventos de anticiclón fuerte, a diferencia de una mayor estabilidad durante el verano.

De los resultados más destacables de las proyecciones se destaca un comportamiento en primavera y otoño que tiende más hacia el verano, así como un desplazamiento del anticiclón hacia el este. Los análisis, en los que se ha empleado técnicas de bootstrap para las tres métricas, muestran diferencias ligeras, sugiriendo cambios en la estructura y comportamiento del anticiclón en el futuro. Los resultados apuntan a un escenario en el que el cambio climático está intensificando la ocurrencia de días de alta presión durante la temporada invernal, así como la estabilidad del tiempo en los meses de verano, lo que resultaría en condiciones más cálidas y secas para las Islas Canarias. El estudio no solo ha indicado la necesidad de examinar más a fondo los efectos de la interacción del Anticiclón de las Azores con otros sistemas regionales, sino también de evaluar las implicaciones en sectores tan cruciales como la agricultura y el turismo.

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1. Introduction. Climate Change and the Azores Anticyclone

Resumen

Esta primera sección proporciona una breve introducción al cambio climático y al efecto particular del anticiclón de las Azores. Explica el efecto de este anticiclón en las Islas Canarias y presenta la necesidad de definir al mismo en el contexto del cambio climático.

1.1 First approach to the Climate Change problem

One of the main problems facing humanity is climate change. It reflects variations in the usual weather conditions experienced by the Earth over periods ranging from centuries to millions of years. Some of the main causes that have been aggravating this change over the last centuries are the combustion of fossil fuels, deforestation or industrial processes that lead to increased concentrations of greenhouse gases in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) states that these types of activities cause an increase in global temperature of about 1.1ºC above the average temperature in pre-industrial times. (Tandon, 2022; Vasconcelos et al., 2023).

Across the globe, human and environmental systems are affected by different factors related to climate change, such as water and food supplies, changing ecosystems and more frequent extreme weather events. In this respect, any change in global atmospheric circulation can lead to modifications in a semi-permanent high pressure system such as the Azores anticyclone, and with it, any alteration in the air circulation associated with this type of systems. In order to understand these variations and to be able to make skilful adaptation plans, it is essential to characterise future climatic scenarios.

1.2 The Azores Anticyclone: An Overview

The Azores Anticyclone, also known as the Azores High, is a large semi-permanent subtropical center of high atmospheric pressure near the Azores, in the Atlantic Ocean. It holds core importance in the climatology of the North Atlantic region and exerts a direct effect on the weather in Europe and North Africa. The Azores High is usually characterized by its strength, position, and extent; these characteristics may vary significantly with both season and broader climatic conditions (Davis et al., 1997; Hernández, 2021).

Tandon (2022) identified the Azores High with an expansion and intensification that has been taking place in the past century and is closely associated with human-induced climate change. This expansion can be linked to enormous alterations in the North Atlantic climate, in particular, changes in precipitation. The gradual expansions of the Azores High prevents the moist air from reaching Southern Europe, thereby keeping the climate generally drier in Mediterranean Europe and producing more rainfall in Northern Europe and the UK.

In WHOI (2022) reanalyses and paleoclimate data are used to find such trends, revealing that, since the beginning of the Industrial Revolution, the frequency of extremely large events of the Azores High has significantly increased. This shift is very important since it might have a big effect on the Iberian Peninsula's winter precipitation and modify the way that agriculture and water resources are used.

1.3 Effects on the Canary Islands

More vulnerable to changes in the Azores High are the Canary Islands since they are within its region. The climate of these islands is conditioned by the subtropical high-pressure system in the North Atlantic. It acts as a regulator of trade winds and general weather patterns in the area.

This anticyclone expansion may vary the climate in the Canary Islands through precipitation and temperature changes. Hernández (2021) revealed that an expansion of the Azores High could lead to a reduced amount of winter rainfall and an increase in dry conditions for the Canary Islands. That would increase existing challenges of water scarcity and desertification; this affects agriculture, biodiversity, and the human settlements on the islands.

In this sense, projected increases in the number of dry days and decreases in the number of wet days for the northeast Atlantic region —the Canary Islands included— will play an essential role in carrying out adaptive measures to reduce the negative impacts on water management and conservation strategies, or sustainable agricultural practices concerning the vulnerabilities related to a changing climate in this territory (Vasconcelos et al., 2023).

2. Data and Methods. Characterizing the Azores Anticyclone: Position and Strength

Resumen

Este capítulo describe en detalle cómo se calcularon los dos parámetros principales del anticiclón: su posición central y su intensidad. Utilizando datos históricos de ERA5 (1980-2014) y proyecciones futuras de CMIP6 (2065-2099), y se describen los métodos basados en percentiles de presión del mar, gradientes de presión y vorticidad, así como los umbrales utilizados para determinar cuándo se considera un anticiclón fuerte.

The location of the Azores High's centre and strength are the two main features that should be highlighted to describe it as effectively as possible. A lot can be learned about the anticyclone's geographical and meteorological impacts by locating its centre. On the other hand, understanding the strength of the anticyclone makes it easier to understand its dynamic features and potential weather patterns.

To analyze and characterize, the Azores anticyclone, historical climate data embedded in the ERA5 reanalysis dataset was used, in particular, between 1980 and 2014, focusing on the North Atlantic region directly influenced by the Azores anticyclone. The ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) encompasses a large set of high-resolution databases that describe the characteristics of the atmosphere, land, and oceans (Hersbach et al., 2020). The spatial window taken ranges from 0º to 60º in latitudes and from -80º to 0º in longitudes, with a resolution of 0.25º provided by the ERA5 reanalysis dataset. Research of climate phenomena may benefit much from the high resolution in time and space of this dataset that allows for an extensive examination of long-term climatic trends as well as weather pattern analysis. In defining climate after a window of thirty years, this extended duration was selected.

The following analysis will focus on seasonal means. This strategy is common for several reasons. First, it filters out the noise that temporary weather patterns bring and thus concentrates on long-term, more stable climate trends. The method makes it possible to detect apparent trends and anomalies of a character that does not appear in daily or monthly data. The Azores High also shows notable seasonal fluctuation. Its position and strength could change greatly over the years because of changes in air circulation. Seasonal analysis will give a clear view of these fluctuations and, hence, help understand how an anticyclone behaves throughout the year.

2.1 Measuring the Center of an Anticyclone

To objectively define the center of the Azores anticyclone, a percentile thresholding method for mean sea-level pressure, gradient magnitude, and vorticity was used. Specifically, the anticyclone center is defined as the area where pressure is at the 90^{th} percentile (highest pressures), and total gradient and vorticity are at the 5^{th} percentile (lowest values). This technique follows atmospheric science principles and statistical stability to obtain a more accurate definition of the core of the anticyclone, similar to what is presented in Olmo and Betolli (2021). As an illustrative example, Figure 2.1 depicts the variety of input variables analyzed to describe the center of the Azores anticyclone for the summer of 2014.

The 90^{th} percentile threshold for MSLP is taken to separate the highest pressure values occurring within the dataset. High-pressure systems like the Azores High are features with relatively higher pressures compared to their surrounding areas. By focusing on the upper 10% range of pressure values, we effectively capture that area at the core of the anticyclone, in which influence from the high-pressure system will be the strongest.

The gradient magnitude of the pressure field indicates the rate of change of pressure across a region. In the center of a high-pressure system, pressure changes minimally, resulting in low gradient values. By selecting the 5^{th} percentile of gradient magnitudes, we focus on areas where the pressure is most uniform and close to its maximum, which is characteristic of the anticyclone's core. Low-gradient regions within high-pressure systems correspond to areas of relative calm and stability. These regions are less influenced by dynamic weather processes such as fronts and cyclones, making them ideal for defining the high-pressure center.

Vorticity measures the rotation of air within the atmosphere. In the core of an anticyclone, air tends to move slowly and more stably, resulting in low vorticity values. The

5^{th} percentile threshold for vorticity ensures that we identify areas of minimal atmospheric rotation, which align with the calm and stable conditions typical of the anticyclone's center. Low vorticity in the center of high-pressure systems reflects the lack of cyclonic or anticyclonic activity, indicating a stable air mass (Clemens et al., 2022). This stability is a defining feature of the anticyclone's core, making vorticity a crucial parameter for its identification.

The ERA5 and CMIP5 data use a regular dimension for each pixel on the globe, so the surface area results in grid points, so a transformation to a more precise measure, such as square kilometers, is necessary. The following approximation for the area of a pixel was used, taking into account the terrestrial latitude at which the pixel is located:

$$Pixel\ Area = \varphi\_resol \cdot (\lambda\_resol \cdot \cos(\varphi))$$

Where φ_resol is the latitude resolution in meters, λ_resol is the longitude resolution in meters and φ is the latitude of the pixel centre.

2.2 Defining a Strong Anticyclone

Precisely defining what a powerful anticyclone constitutes is essential to understanding the impact of the Azores High on the regional climate and its variability. The expansion of the high-pressure area, the maximum of the mean sea level pressure (MSLP) within that area, and the difference in the pressure gradient value between the center and the high-pressure threshold are three important metrics that can be used to assess the strength of a high-pressure system.

The spatial region under investigation would be one where the MSLP is higher than the 1020 mbar threshold. This threshold point is not chosen at random. In Pezza and Ambrizzi (2003) this value is identified as a significant indicator of prominent anticyclonic conditions. This threshold enables to differentiate between areas with moderately high

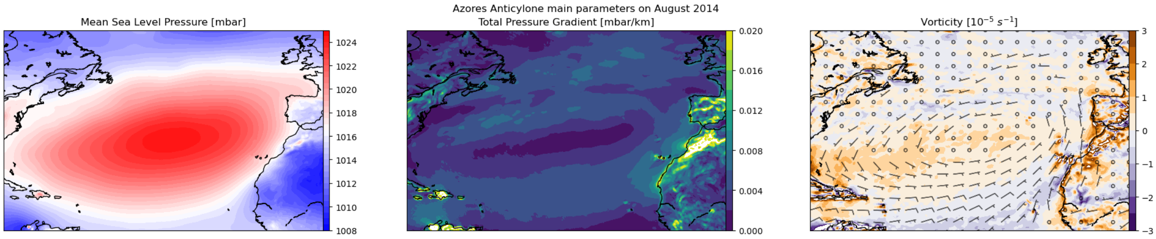

Figure 2.1 Mean values of the variables (MSLP, total pressure gradient and vorticity, from left to right) evaluated to define the center of an Anticyclone for the Summer of 2014

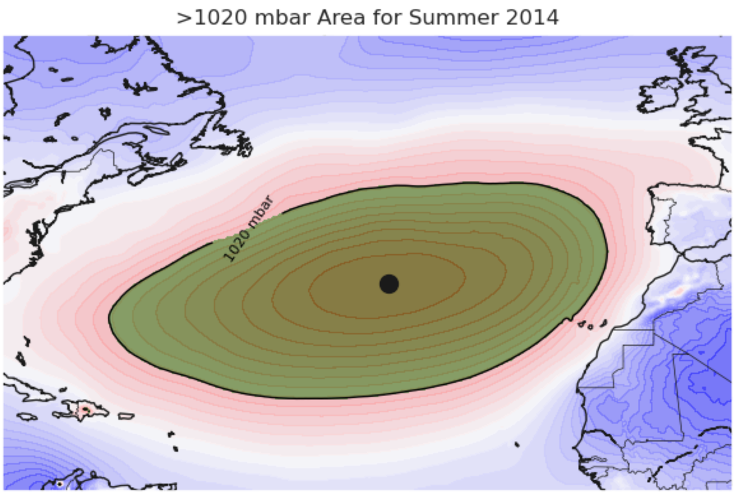

Figure 2.2 Region over 1020 mbar of the Azores Anticyclone for the Summer of 2014.

pressures and regions where pressure is high enough to have a significant impact on regional climate. Bielec-Bąkowska and Widawski (2018) also considers that the 1020 mbar pressure is high enough to highlight the presence of robust anticyclones and distinguish them from high-pressure systems not strong enough to have a climatic influence. Therefore, we can define the >1020 mbar area covered by the system to be the first metric to define the strength, where a great area of high pressure indicates a dominant and potentially influential anticyclone. As an example, figure 2.2 shows this area of study for the summer of 2014.

Another key feature of the study would be the maximum value of the MSLP value inside that area. A high maximum MSLP value would be an indicator of a more intense and persistent high-pressure system. This kind of anticyclones may have prolonged effects on regional climate, maintaining dry and stable conditions during longer periods.

The difference in gradient between the system center and the mean gradient value at the 1020 mbar threshold is the last parameter used to determine the intensity of an anticyclone. The gradient difference serves as an indicator of the anticyclone's robustness since a more pronounced gradient denotes a more concentrated high-pressure system, which increases atmospheric stability and inhibits clouds and precipitation.

To classify an anticyclone as strong it needs to overcome the highest quartile at the three metrics when compared with the data of study. The selection of the highest quartile as a threshold is because it represents the 25% of highest values among a data set, which ensures that only the most significant and extreme events are being considered as strong.

2.3 Determining future changes in the Azores anticyclone

To evaluate possible future changes in the Azores anticyclone by the end of the 21st century, in particular from 2065 to 2099, the same methodology as in sections 2.1 and 2.2 will be applied to the Coupled Model Intercomparison Project Phase 6 (CMIP6) dataset, which provides high-resolution climatic projections (Eyring et al., 2016). In particular, the model taken has been the GFDL with the worst-case scenario, the RCP8.5, taking the same spatial window as for ERA5 (0º to 60º in latitudes and -80º to 0º in longitudes) but with a lower resolution, 1º in latitudes and 1.25º in longitudes. Therefore, in order to make a direct comparison of the differences between past and future results, it was also used the CMIP6 database with historical data (1980-2014), then being both at the same resolution. With these projections, it will be possible to interpret the possible variation in the position of the centre for the different seasons, as well as the frequency with which strong anticyclones are found. For this interpretation of strong anticyclones, new thresholds will be calculated for each metric, so it will also be possible to analyse how these thresholds vary, and whether they are more restrictive or more accessible.

2.3.1 Bootstrap Analysis

After obtaining the future results, a good way to analyse whether there are variations, and if so, whether these are substantial, is through the Bootstrap method. Bootstrap analysis is a powerful and flexible statistical technique that allows to estimate the distribution of a sample. It is based on the resampling with replacement to generate multiple bootstrap samples, that are essentially simulated replicas of the original dataset. These samples are then used to calculate the statistical distribution of interest, which allows to evaluate the uncertainty and variability without relying on strict assumptions about population distribution (Belío Miranda, 2020).

Therefore, in the framework of this work, this type of analysis has been used in two situations. The first one is to find differences in the probabilities of finding the centre of the anticyclone in each pixel, for each season. Bootstrap samples, past and future, of each pixel are generated with 1s and 0s (presence and non-presence of the centre). Each sample is averaged and the difference between the past and future samples is calculated, repeating this process 1000 iterations, to compensate for the randomness that exists in the generation of the bootstrap samples. The average of all these iterations will be the value of the variation in probabilities of finding the centre in that pixel.

The second situation in which this analysis has been used is for each of the metrics presented in the section 2.2. This gives the results of how these metrics have varied between the past and the future for each season.

3. Results. Position and Strength of the Azores Anticyclone in the Recent Past

Resumen

Los resultados de utilizar las definiciones de centro y fortaleza del anticiclón se muestran en esta sección. Se destaca la gran variabilidad observada para el invierno y la relativa estabilidad observada para el verano en cuanto a los comportamientos estacionales. Los eventos de anticiclón fuerte se identifican y se comparan con los límites establecidos.

3.1 Seasonally Azores Anticyclone Centers

Given the explained criteria to define the center of a high-pressure system in section 2.1, it is shown in figure 3.1 the overlap for all centers calculated for Winter, Spring, Summer and Fall for the Azores High through all the years of evaluation.

During the Wintertime, the Azores High center is generally positioned more to the North and East and locates itself in an area where it finds more relief, such as the Iberian Peninsula and North of Africa. It is also the season of the year when the high-pressure system is more elongated and spread out, reflecting its influence over a broader area. It is also remarkable the indeterminacy that exists when generalising the position of the centre for this case since a large area of uncertainty is apparent. During this season, the Canary Islands receive more steady weather due to the proximity of this anticyclone. However, the islands can occasionally be influenced by passing Atlantic storms, resulting in wetter conditions.

In Spring, the centre begins to move towards a more northerly position, with hardly any presence in the continental zone. The system obtains a more circular and consolidated shape, and less variability in the position is noticeable. For the Canary Islands, this translates into a transition to drier and warmer conditions. The influence of the Azores High becomes more dominant, reducing the likelihood of stormy weather and leading to more settled conditions.

During Summer the centre of the anticyclone is in its most easterly position, covering purely oceanic areas. It is remarkable its low variability for different years, which shows a constant periodicity to be able to define the centre of the Azores High year after year with a higher index of determination. The strong presence of the Azores High in summer is associated with stable, warm, and dry conditions across much of Southern and Western Europe. For the Canary Islands, this position and structure of the anticyclone prevents them from being affected by low-pressure systems from the west.

In the Fall, the Azores anticyclone begins to return to a more northerly and easterly position. It loses the more circular and stable shape it had gained in previous seasons, expanding into a more elongated shape. There is also an increase in year-to-year variability. This new position gives the Canary Islands a higher likelihood of rainfall, as a consequence of the high-pressure system's influence being decreased.

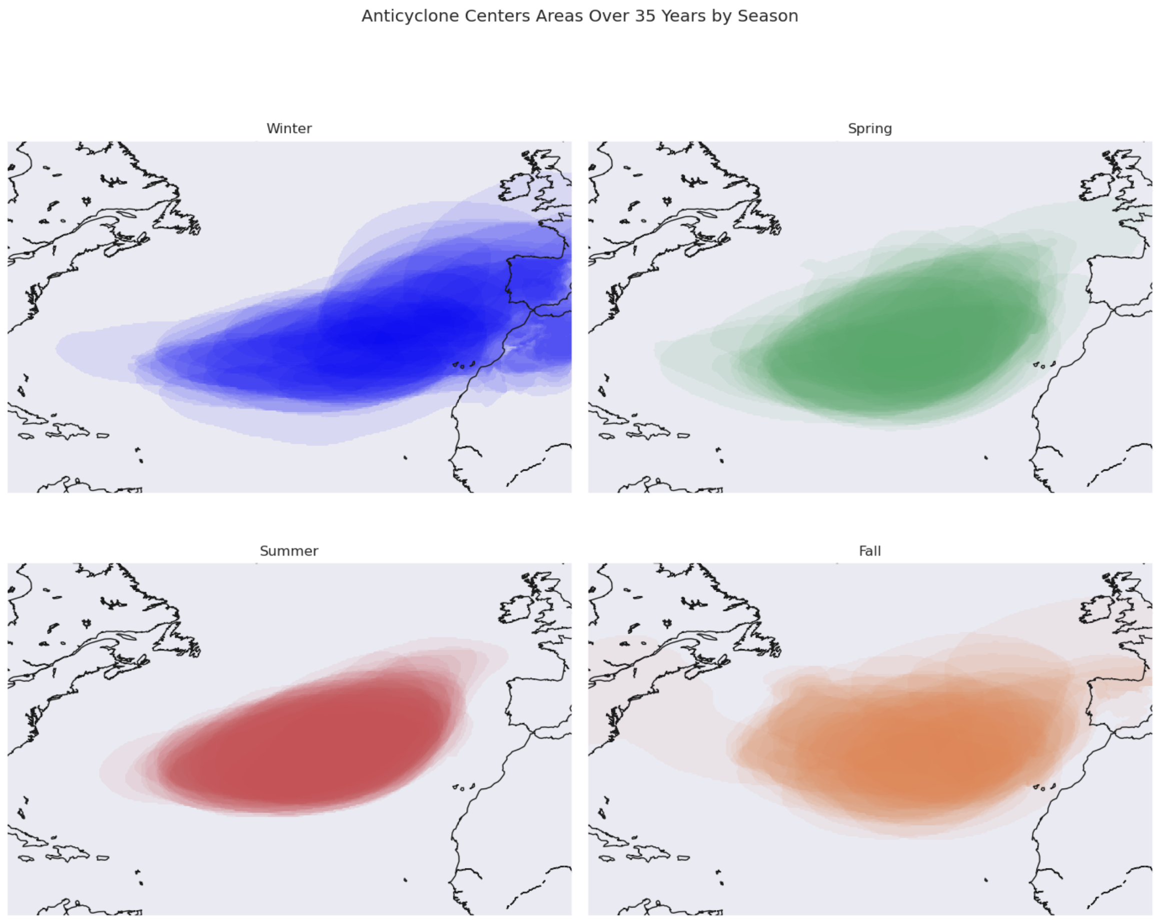

Figure 3.1 Overlapping Centers of the Azores High for Winter, Spring, Summer, and Fall (1980-2014)

In Appendix A a more detailed view of every center across the 35 years, year by year, is provided. For instance, it suggests a progressive eastward and slightly northward shift in the Azores High's position over the summer. This pattern might be a sign of more significant climate changes, such as global warming, which might be affecting high-pressure system behavior and atmospheric circulation patterns.

Combining these criteria—high pressure (90^{th} percentile), low gradient magnitude (5^{th} percentile), and low vorticity (5^{th} percentile)—provides a comprehensive and robust method for defining the center of the Azores High. This integrative approach ensures that the identified center is not only a region of high pressure but also an area of atmospheric stability and minimal dynamic activity.

In addition to overlapping the anticyclone centers, probability maps (figure 3.2) were created to display the regions in which it is more likely to locate the system's center for each season. These probabilities were computed as a function of how frequently the anticyclone center was located in each grid point throughout the study period. These results only corroborate the previously described stability of the summer months. In this season, there is a very high probability of finding its centre in a well-defined area. This is the opposite of what is observed in winter, where the variability is high, and therefore the probability is much more dispersed.

By representing these probabilities in a three-dimensional way (figure 3.3), a clearer and more detailed visualisation is provided. These 3D plots show a very sharp and concentrated structure for the summer in contrast to the amplitude and instability that characterises the winter probability distribution. The spring and autumn seasons are in an intermediate state, characterising them as transitional seasons.

3.2 Historical Strong Azores Anticyclone Seasonal Events

In line with the definition presented in section 2.2, all seasons were subject to the same definition from 1980 to 2014. This was used to calculate the thresholds for the three characteristic metrics that would define when an Azores anticyclone could be considered seasonally strong. The results can be found in Figures 3.4-3.15.

Winter (figures 3.4, 3.6, 3.8) is the season in which the same case is most often above the threshold for the three metrics analysed, such as the winters of 1981, 1989 or 2014, among others. There is no general trend that stands out among the three indicators, but the variability and deviation from the trend line that exists for all of them is notorious. This variability can be attributed to the influence of various atmospheric circulation patterns, such as the North Atlantic Oscillation (NAO) (Rashid et al., 2012).

In summer (figures 3.10, 3.12, 3.14), there are also numerous cases of strong anticyclones, such as in 1990, 1996 and 2002. Here a slight downward trend can be seen in all three variables, and, unlike the winters, there is noticeable stability, and low deviation, around the trend line, a behaviour of stability that was already seen in the case of the position of the centre of the anticyclone.

For the spring (figures 3.5, 3.7, 3.9) and autumn (figures 3.11, 3.13, 3.15) seasons there is only one strong anticyclonic event, that is the spring of 2002, which indicates that these are not times of extreme anticyclonic events, but rather transient ones. This is also shown in their variability and deviations from the trend lines, which are at a middle point between the typical oscillation of winter and the characteristic robustness of summer.

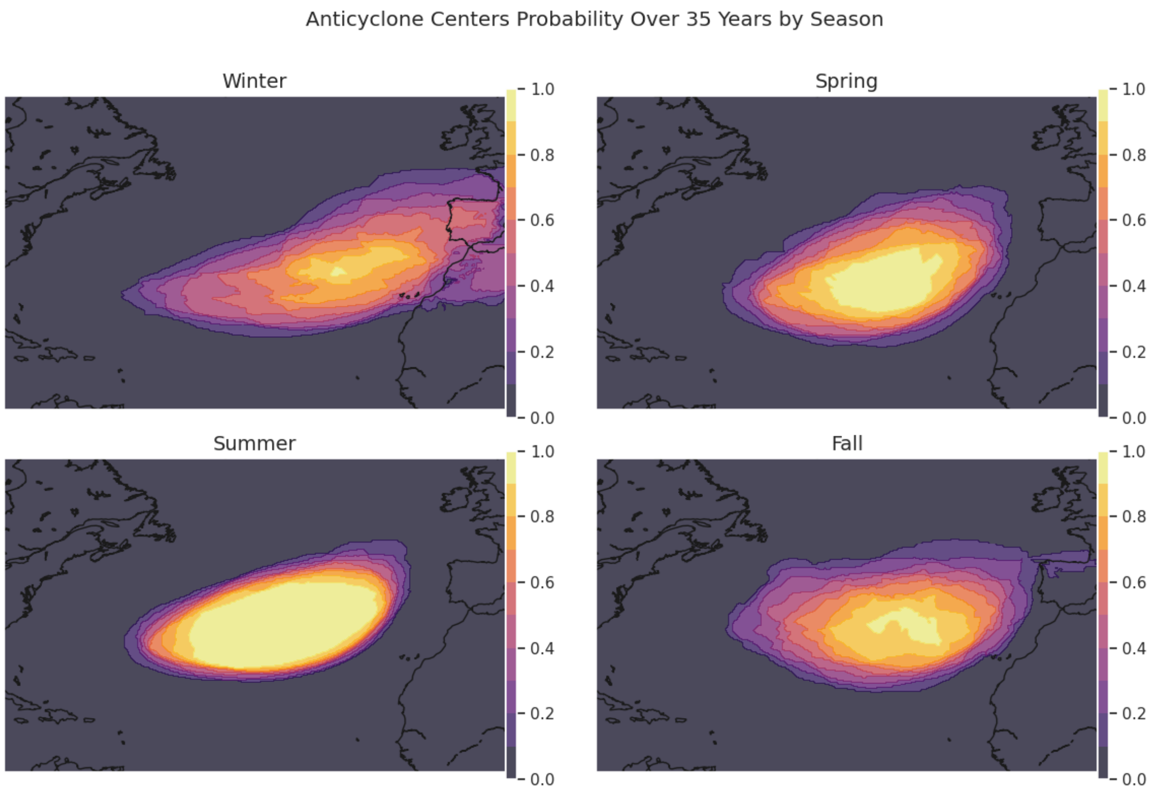

Figure 3.2 Probabilities of the center position of the Azores High by seasons (1980-2014)

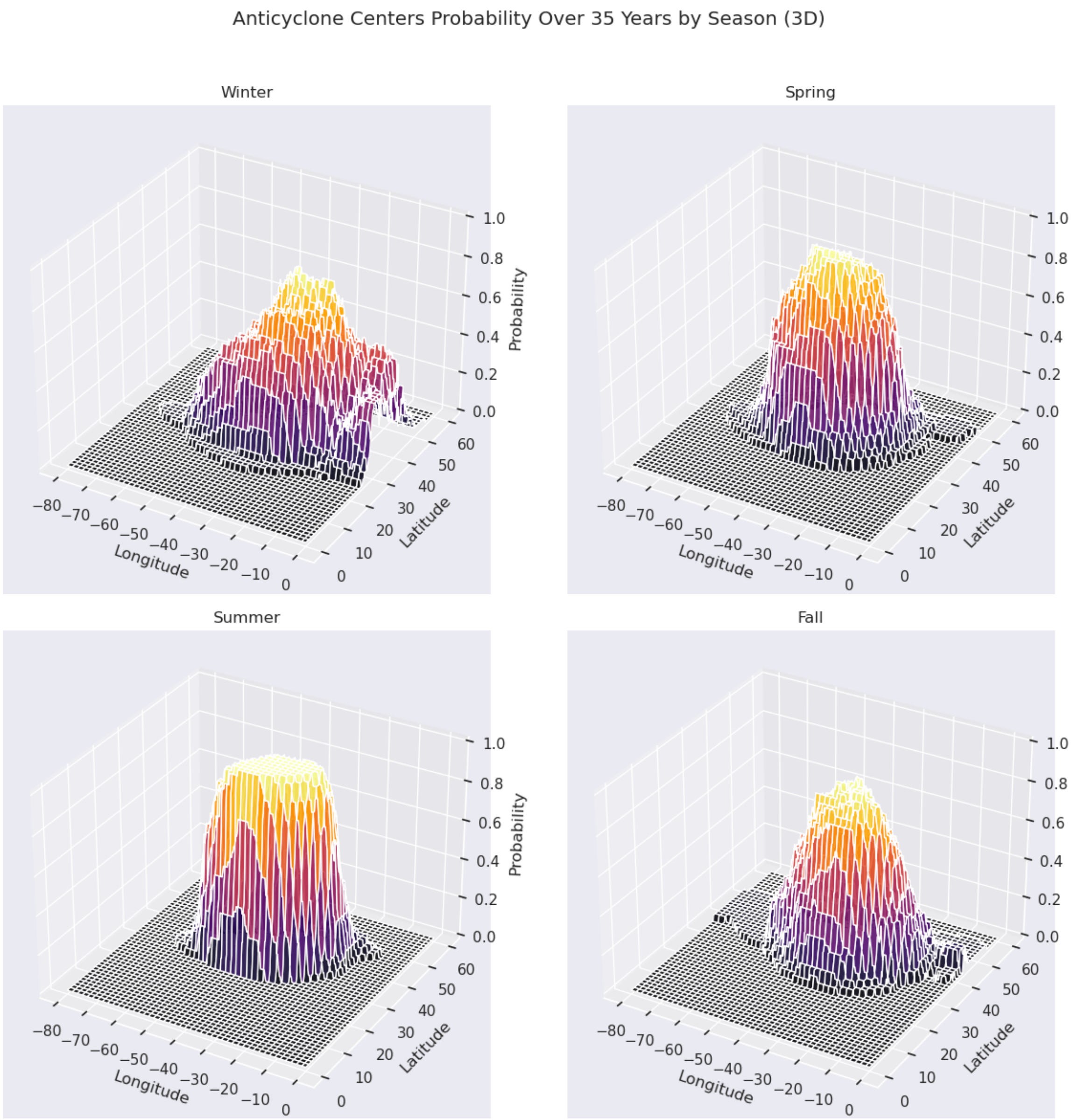

Figure 3.3 3D representation of the probabilities of the center position of the Azores High by seasons (1980-2014)

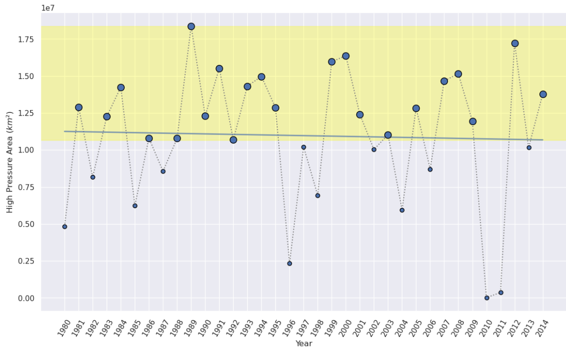

Figure 3.4 High Pressure Area - Winter

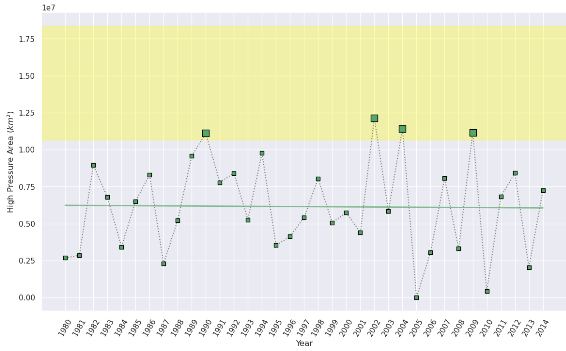

Figure 3.5 High Pressure Area - Spring

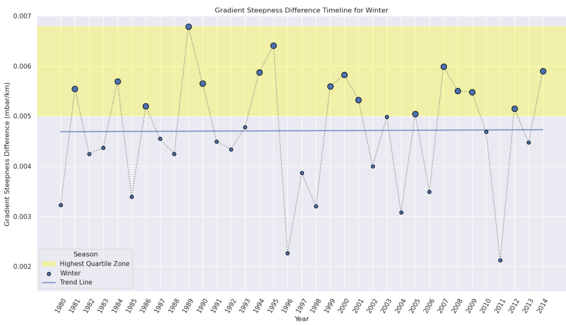

Figure 3.6 Gradient Steepness - Winter

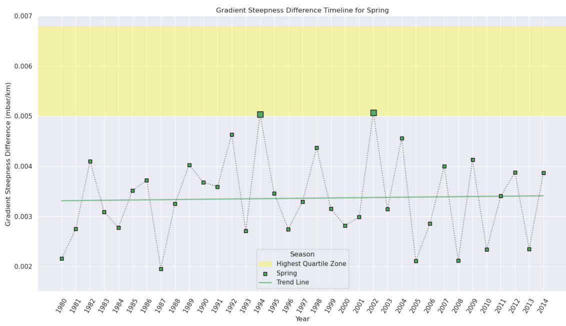

Figure 3.7 Gradient Steepness - Spring

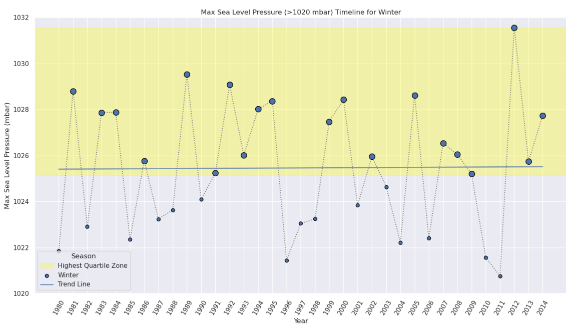

Figure 3.8 Max MSLP Value - Winter

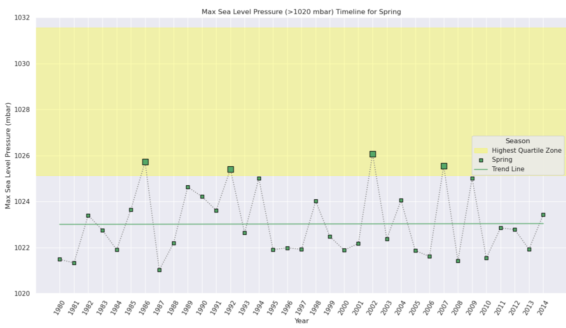

Figure 3.9 Max MSLP Value - Spring

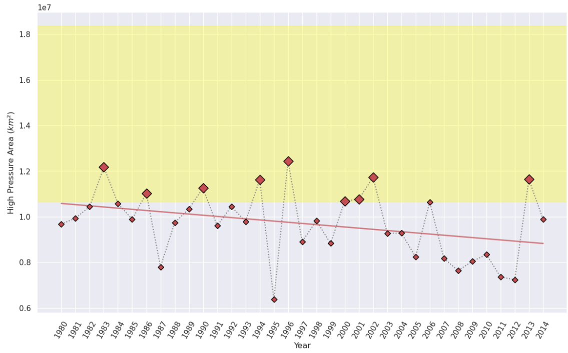

Figure 3.10 High Pressure Area - Summer

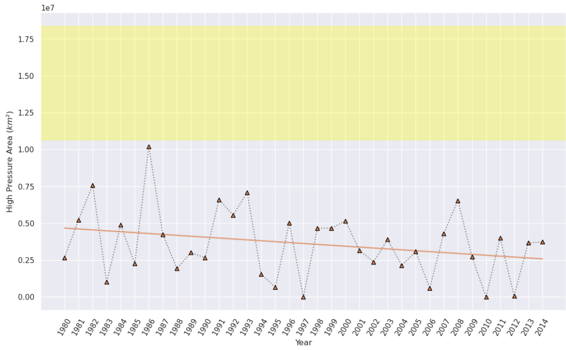

Figure 3.11 High Pressure Area - Fall

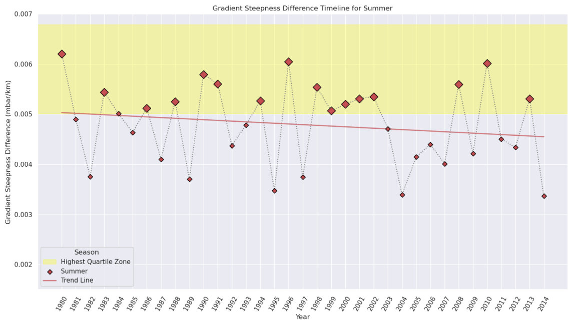

Figure 3.12 Gradient Steepness - Summer

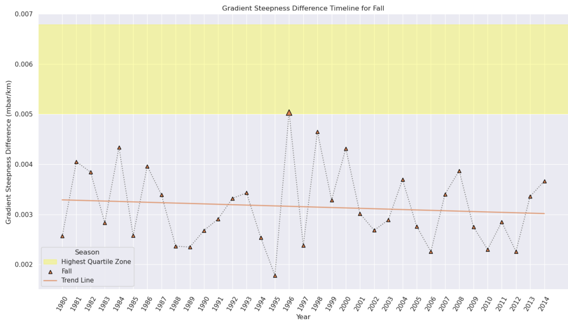

Figure 3.13 Gradient Steepness - Fall

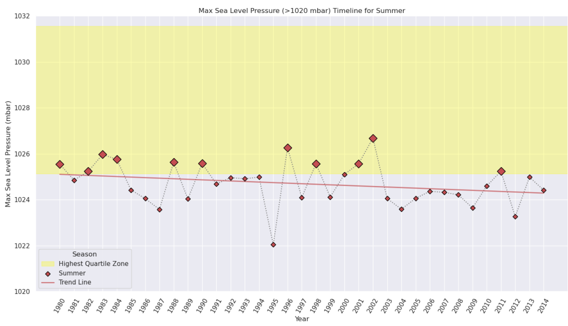

Figure 3.14 Max MSLP Value - Summer

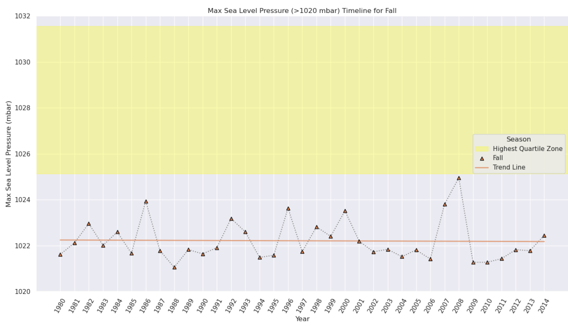

Figure 3.15 Max MSLP Value - Fall

4. Future Projections of the Azores Anticyclone. Comparison with Present Features

Resumen

En este capitulo se utilizan los pronósticos CMIP6 (2065-2099) para predecir el comportamiento futuro del anticiclón. La intensidad de los eventos y la ubicación de los centros se comparan con los eventos del pasado reciente. En el verano, hay una mayor estabilidad, mientras que en la primavera y el otoño hay un comportamiento que tiende a alargar los veranos. Las pruebas de boostrap muestran señales de cambios significativos en la inclinación del gradiente, lo que generalmente indica una tendencia hacia un régimen de clima más estático con una posibilidad de clima más cálido y seco.

4.1 Future Azores Anticyclone Center Location

By calculating the probabilities of the center position (figure 4.1) certain changes are beginning to be appreciable (the position of the centre for every individual year and season can be analysed in the figures in the appendix B). At first glance, there is no apparent change in the location or area of extension of the anticyclone for any of the seasons. If the winters are compared, the probability of finding this centre over the Iberian Peninsula is lost, something that was present in recent cases, but there is still no notable area where the presence of the centre of the anticyclone can be guaranteed with probabilities between 0.9-1.0. Also, the variability is less diffuse and falls within a smaller range of latitudes. If, on the other hand, the probabilities for summer are compared, it stands out that they are practically the same, both in extension and location, and it is still a fairly stable season throughout the years.

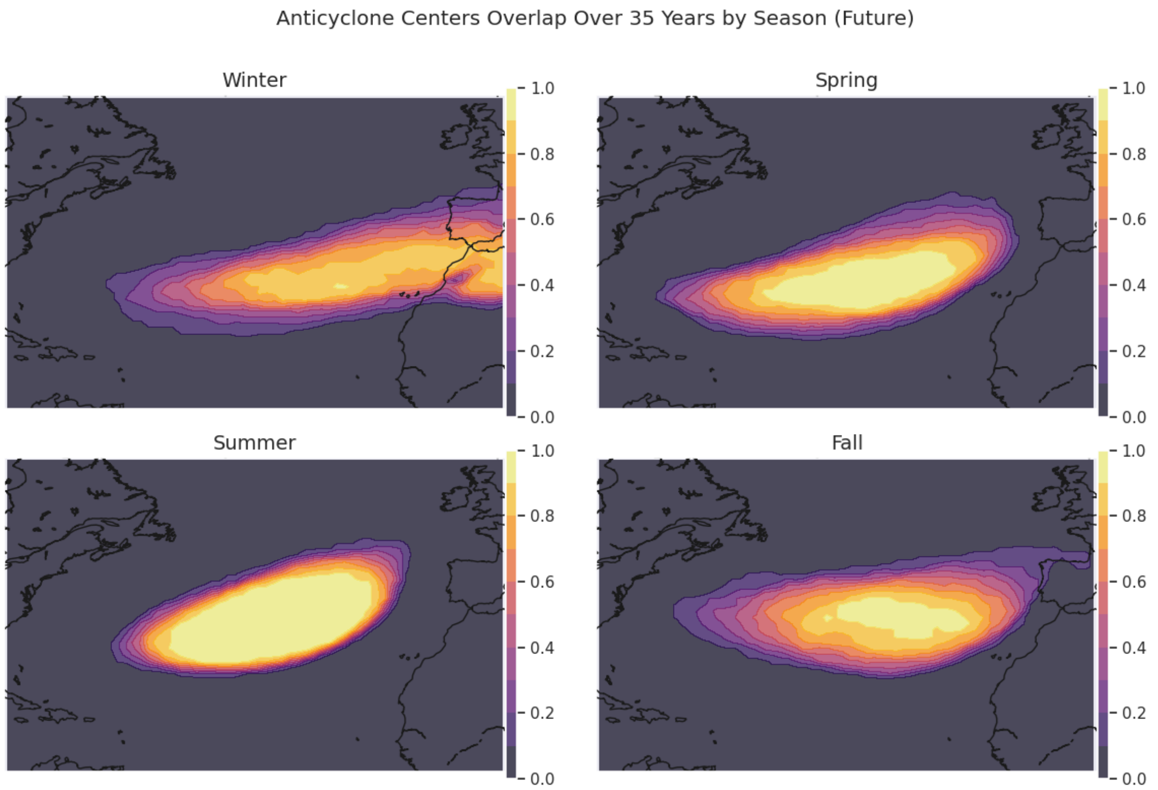

Figure 4.1 Future probabilities of the center position of the Azores High by seasons (2065-2099)

However, the most notable difference is found in autumn and spring, especially in the latter. Although they are still transitional seasons between summer and winter, we can see how they tend to behave more like summer, with positions more towards the east and with an extension of the area more characteristic of this season than of winter. In fact, the representation of spring probabilities is quite similar to that of recent years in summer. This gives a first idea of the possibility of longer summers at the end of the century.

These conclusions in the comparison are also quite noticeable when looking at the 3D representation of the probabilities (figure 4.2). Despite the drop in resolution, it can be seen that the winter position would still be variable, but in a narrower range of latitudes. The summer probabilities continue to show this stability and robustness, while the spring and autumn probabilities lose variability and begin to be more similar to the summer graph.

4.1.1 Differences in the probabilities of the center position

After doing the bootstrap (section 2.3.1) pixel by pixel calculating the differences in the probabilities of finding the centre in the same pixel, these are the final results. It can be seen that for all the seasons the centre is more present in positions further north. It is striking

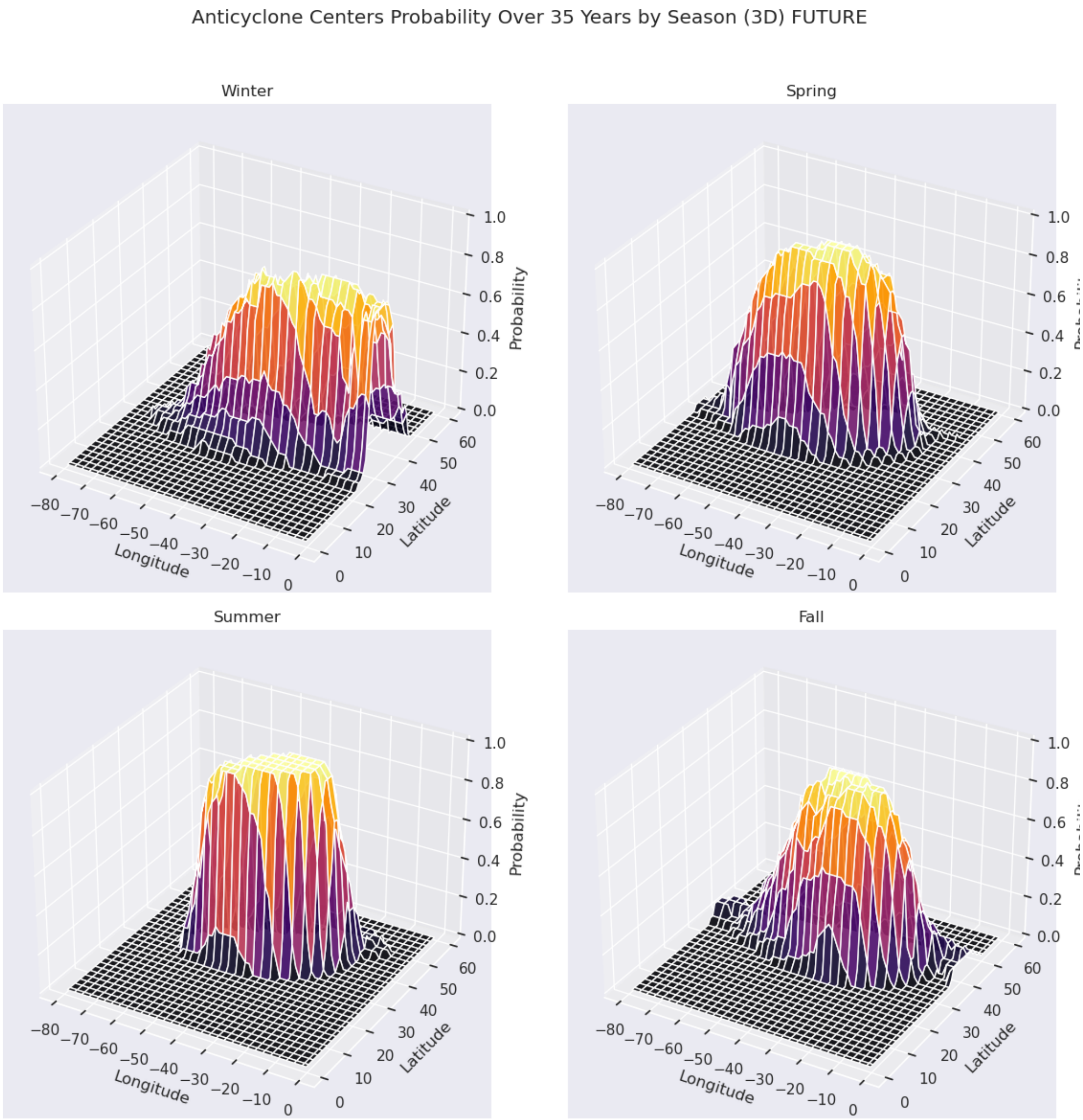

Figure 4.2 3D representation of the future probabilities of the center position of the Azores High by seasons (2065-2099)

how for winter, spring and autumn, the centre tends to be more centred, especially for the last two, where the presence of the centre is increasingly clearer in a purely oceanic position. The summer months show hardly any variation, rather than clarifying its solid structure. In fact, in the centre itself, no differences are noticeable.

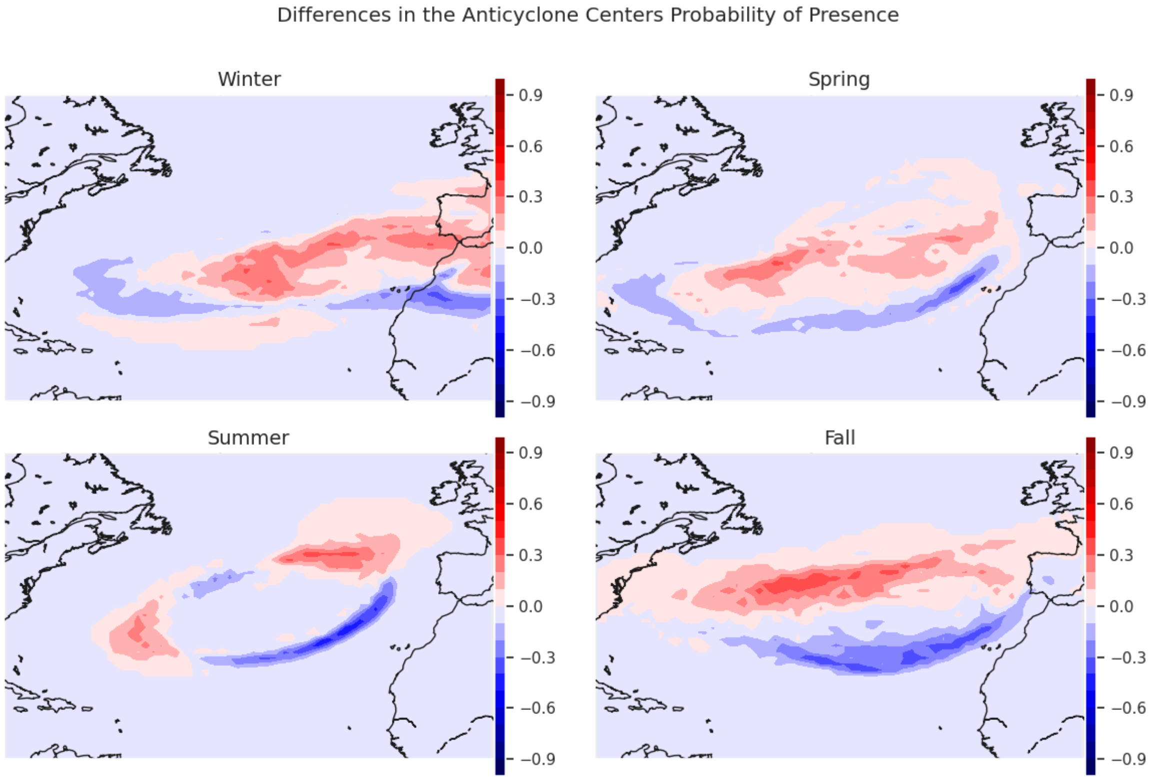

Figure 4.3 Differences in the probabilities of the center position between past and future

4.2 Future Projection of Strong Azores Anticyclone Events

The figures 4.4-4.15 show the results after applying the definition described on 2.2 for the future projection dataset. The first thing to note to compare these results with those of recent past data is the thresholds. Both the expansion areas and the maximum MSLP thresholds remain at similar values, around $1 \sim 1.2 \cdot 10^7\ km^2$ for the areas, and around 1025 mbar for the maximum pressure values. However, there is an appreciable variation in the threshold for the difference in gradient steepness values, which is considerably lower, making it more accessible for certain events to exceed this threshold. What this variation translates into will be discussed later on.

Looking at the future seasons and comparing these results with those studied in the section 3.2, very similar season-by-season behaviour is highlighted, with these very variable winters, with a notorious deviation from the trend lines, but with several values above the threshold in the three metrics, giving rise to several strong anticyclone events. On the other hand, summers are much more stable year after year, with also various examples of strong events. The only difference to note, although it is quite significant, is that, for these seasons, the trend lines start to slope upwards.

For future springs and autumns, it can be observed what has already been discussed in the previous section (4.1). Despite being transitional seasons, they begin to have a pattern more similar to that of summer, not only in the behaviour of the events year after year, but also in the fact that several events in autumn, but especially in spring, begin to exceed the thresholds, something that was more difficult to find with the data from the recent past.

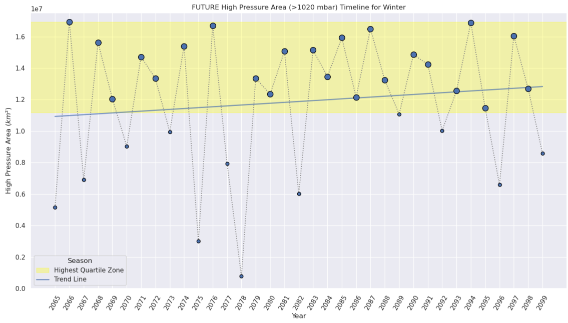

Figure 4.4 Future projection High-Pressure Area - Winter

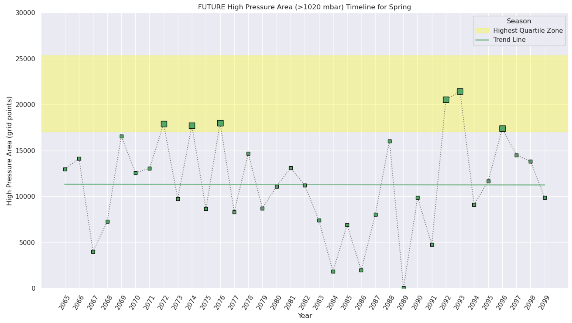

Figure 4.5 Future projection High-Pressure Area - Spring

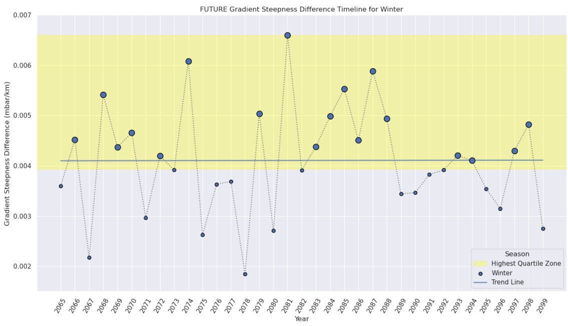

Figure 4.6 Future projection Gradient Steepness - Winter

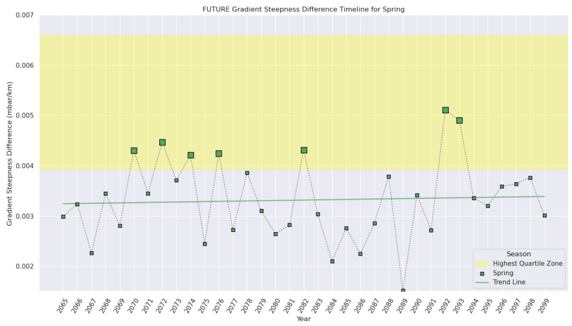

Figure 4.7 Future projection Gradient Steepness - Spring

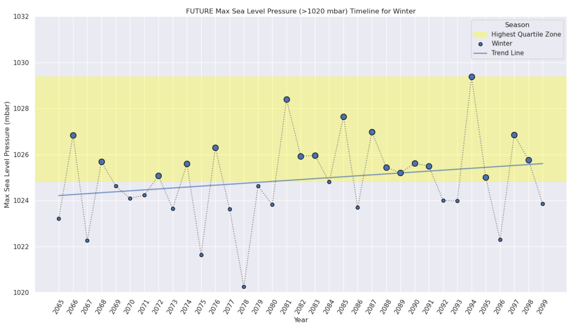

Figure 4.8 Future projection Max MSLP Value - Winter

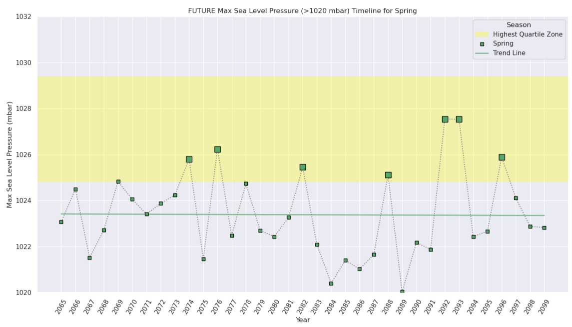

Figure 4.9 Future projection Max MSLP Value - Spring

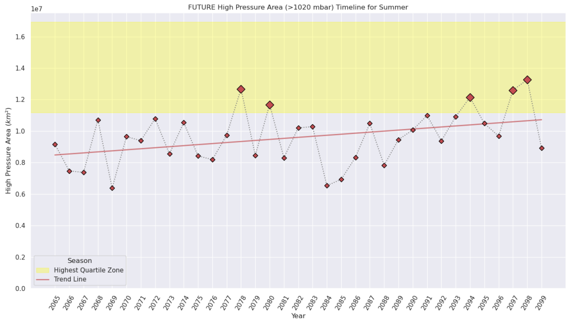

Figure 4.10 Future projection High-Pressure Area - Summer

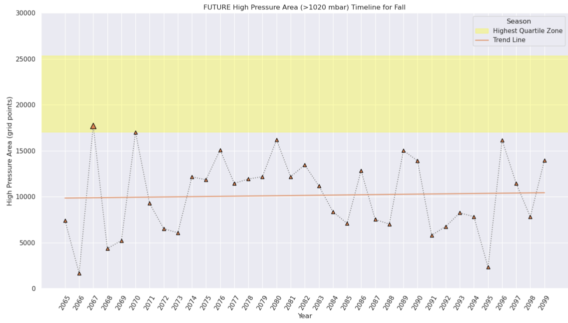

Figure 4.11 Future projection High-Pressure Area - Fall

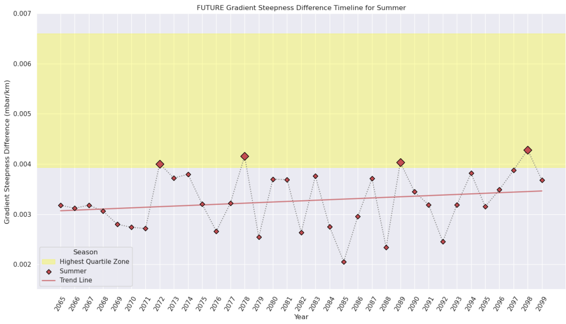

Figure 4.12 Future projection Gradient Steepness - Summer

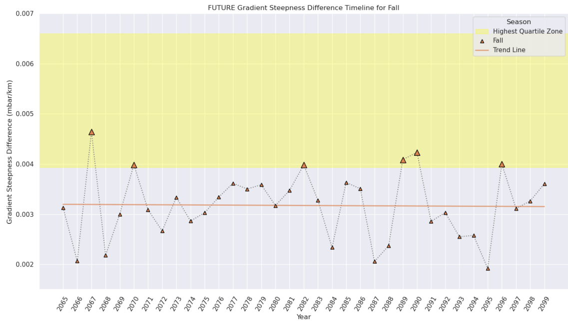

Figure 4.13 Future projection Gradient Steepness - Fall

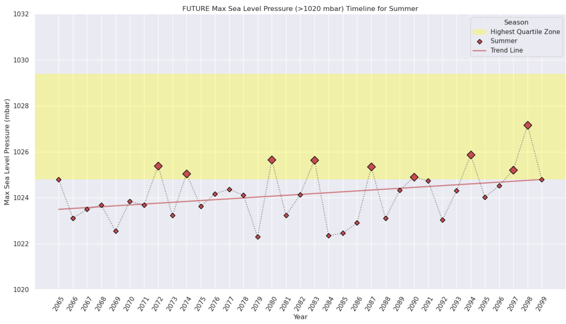

Figure 4.14 Future projection Max MSLP Value - Summer

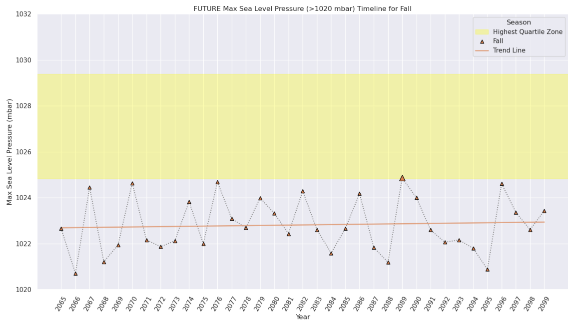

Figure 4.15 Future projection Max MSLP Value - Fall

4.3 Results on the Bootstrap Method

Table 4.1 presents the results of applying the Bootstrap method to all three metrics for every season. Figure 4.16 also gives a clear graphical visualisation of these results.

The metric that shows the least evolution is the maximum pressure. The average differences oscillate in values of thousandths of a mbar when dealing with values in the

	Gradient Steepness ($mbar/km$)		Max MSLP ($mbar$)		High Pressure Area (km^2)	
Season	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.
Winter	$-6.3 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$	-0.6	0.6	$9 \cdot 10^5$	$10 \cdot 10^5$
Spring	$-0.4 \cdot 10^{-4}$	$1.9 \cdot 10^{-4}$	0.4	0.4	$14.4 \cdot 10^5$	$8 \cdot 10^5$
Summer	$15.2 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	-0.56	0.25	$-1 \cdot 10^5$	$4 \cdot 10^5$
Fall	$0.2 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	0.60	0.24	$30 \cdot 10^5$	$6 \cdot 10^5$

Table 4.1 Bootstrap results (mean difference between future and recent past, and standard deviation)

order of approximately 1020 mbar. It is therefore not possible to refer to a change in this magnitude.

As far as the area of expansion of high pressure is concerned, for the winter, spring and summer seasons, very slight variations are observed (increasing for the first two, and slightly decreasing for summer), but these are so small that statistically it cannot be said that there is any significant change. However, in autumn there is an important evolution. The bootstrap results show, for this season an average growth between the areas of 1980-2014 and those of 2065-2099 of approximately 3 million km^2, which is quite high, considering that the average of the areas for this season in the most recent past years was between 2 to 6 million km^2 approximately.

But the variable that is expected to change the most is undoubtedly the gradient steepness. Not so much for the spring or autumn months, but for winter, $(-6.3 \pm 2.5) \cdot 10^{-4}$ mbar/km and especially for summer, $(15.2 \pm 1.6) \cdot 10^{-4}$ mbar/km. These changes are notoriously high when dealing with values averaging around $50 \cdot 10^{-4}$ mbar per km.

To summarise, the predicted variations in the strength and intensity of the Azores anticyclone are as follows: maximum pressure values are practically the same, the areas of expansion of the high-pressure area are slightly higher in autumn, the area of influence for the rest of the seasons will be similar, but despite all this, the steepness of the gradient will have a much less pronounced slope. What does this suggest in terms of the anticyclone's potential influence in the future?

Lower gradient steepness results in less pronounced pressure changes within the anticyclone for the same area and maximum pressure value. As a result, atmospheric conditions become stagnant, which decreases the frequency of dynamic weather patterns like cold air fronts and thunderstorms. As a result, there will be calmer weather, which could lead to greater heat waves and droughts more frequently. Spring and fall would become simple continuations of summer, and winters would become drier and more stable.

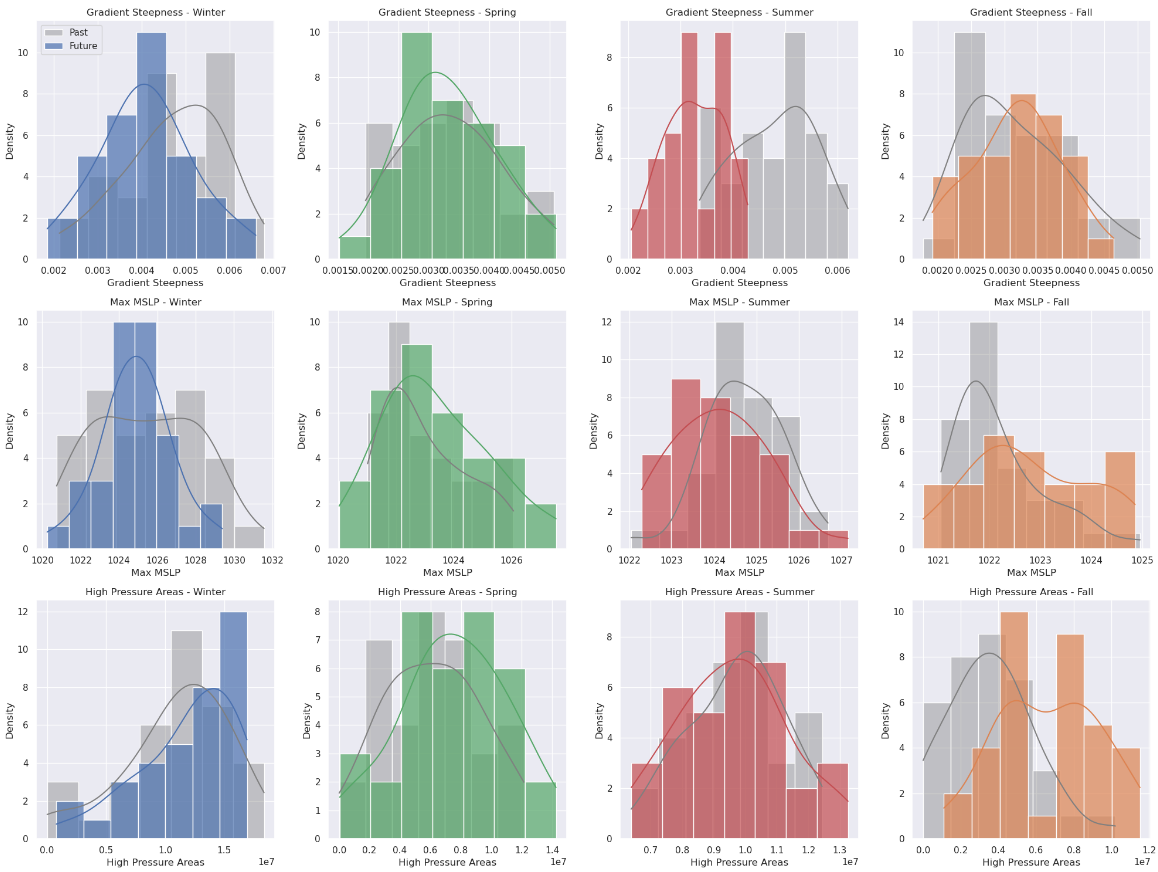

Figure 4.16 Distributions of gradient steepness, maximum MSLP values, and high-pressure areas for recent past and future projections by season.

5. Conclusions and Insights

Resumen

Esta sección resume los resultados más importantes del estudio, las implicaciones para el clima regional y las cuestiones que podrían ser investigadas en el futuro. Se concluye que a finales del siglo XXI, es probable que el Anticiclón de las Azores ejerza un mayor control sobre la estabilidad y los eventos extremos en las Islas Canarias.

This study has provided a detailed characterisation of the Azores anticyclone in the recent past (1980-2014) and projects its future evolution for the end of the century (2065-2099).

It has been observed that the position of the centre of the anticyclone shows significant seasonal variability. In winter, the centre tends to be closer to the Iberian Peninsula, while in summer it moves westwards over the North Atlantic. The results indicate that the area covered by pressures above 1020 mbar has shown a tendency to increase in the future, especially in spring and fall. This suggests a strengthening of the anticyclone in these seasons. The maximum MSLP values show no apparent changes, however, the difference in gradient slope between the centre and the edge of the anticyclone has shown a large decrease, suggesting a broader and less pronounced anticyclone in the future.

A stronger and more widespread anticyclone can result in drier and warmer winters on the Iberian Peninsula and the Canary Islands. This can also lead to an increased frequency of extreme temperature events in the form of heat waves, especially in summer. These results would intensify drought conditions, having a substantially negative impact on agriculture and water resources. On the other hand, precipitation patterns in the North Atlantic would also be affected, with reduced rainfall in southern Europe and increased precipitation in the northern area due to the shift of the wind flow.

Exploring how this strengthening of the anticyclone interacts with other weather systems, such as the North Atlantic Oscillation (NOA), could be an area for future research, as it would give a better understanding of weather patterns on a larger scale. Also, future studies should address adaptation strategies for regions which are severely affected by the dynamics of the Azores anticylone.

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Azores Anticyclone centers by seasons (1980-2014)

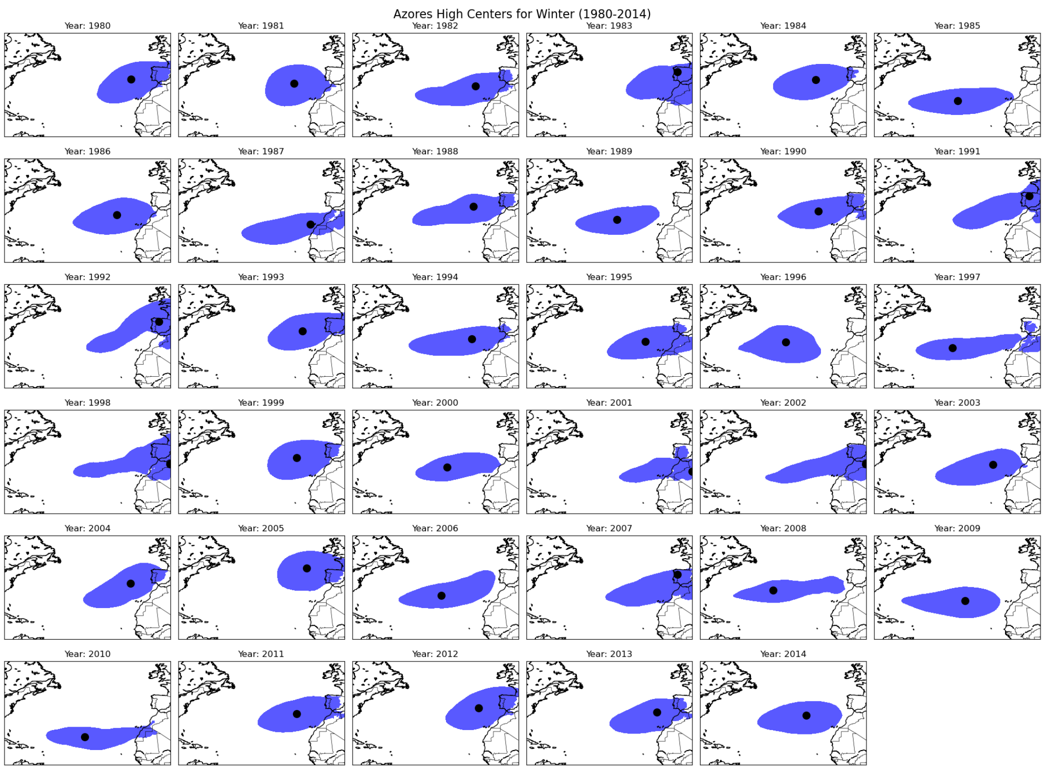

Figure A.1 Azores High Centers for Winter (1980-2014)

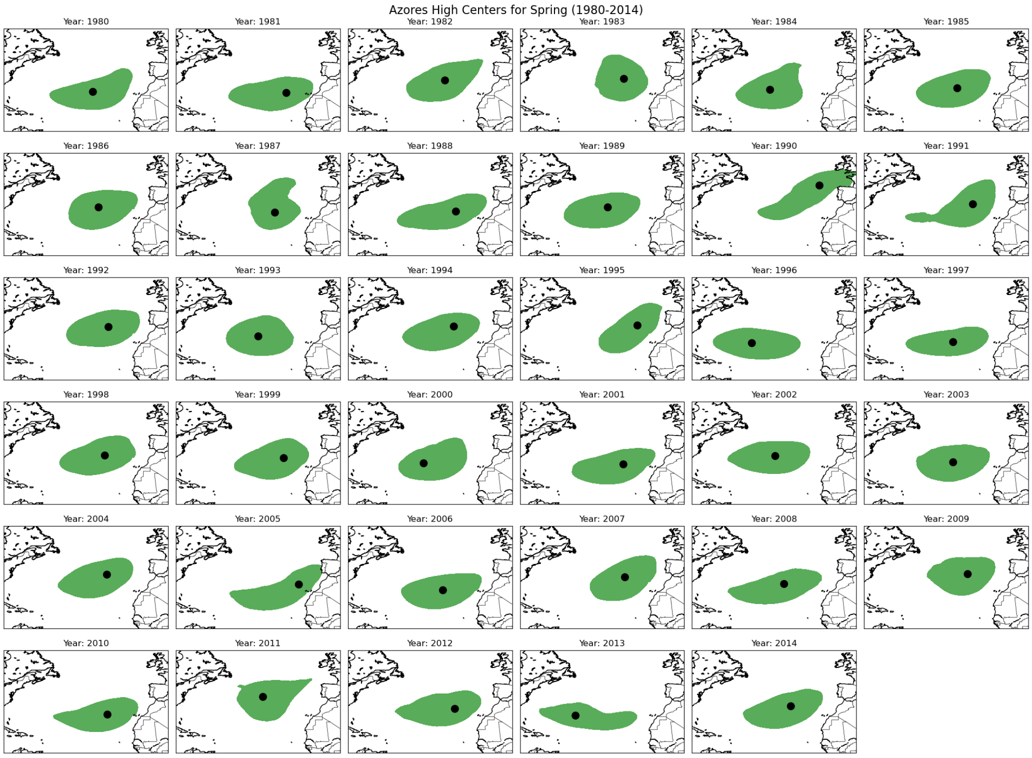

Figure A.2 Azores High Centers for Spring (1980-2014)

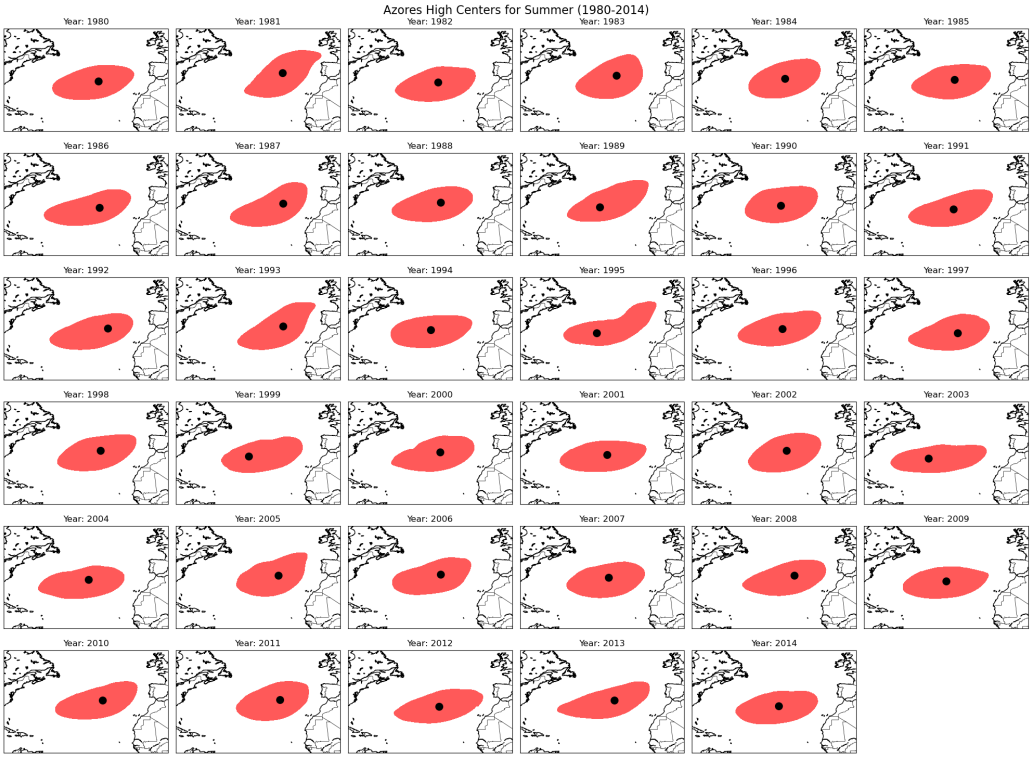

Figure A.3 Azores High Centers for Summer (1980-2014)

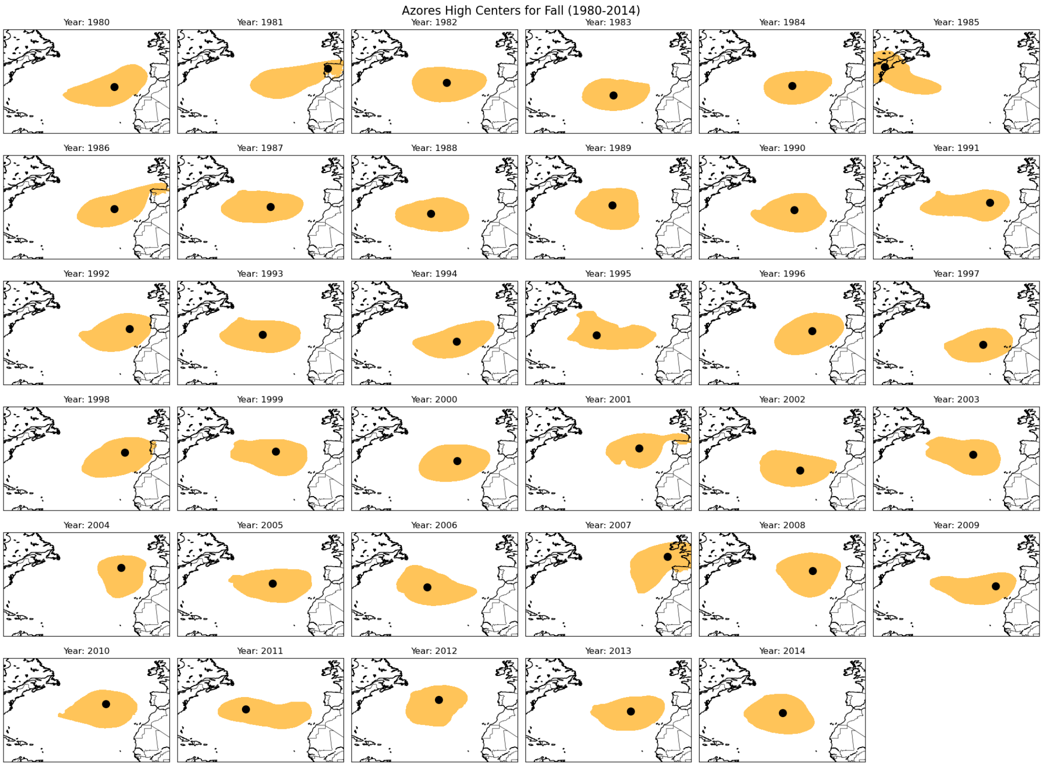

Figure A.4 Azores High Centers for Fall (1980-2014)

Azores Anticyclone CMIP6 Future Projection centers by seasons (2065-2099)

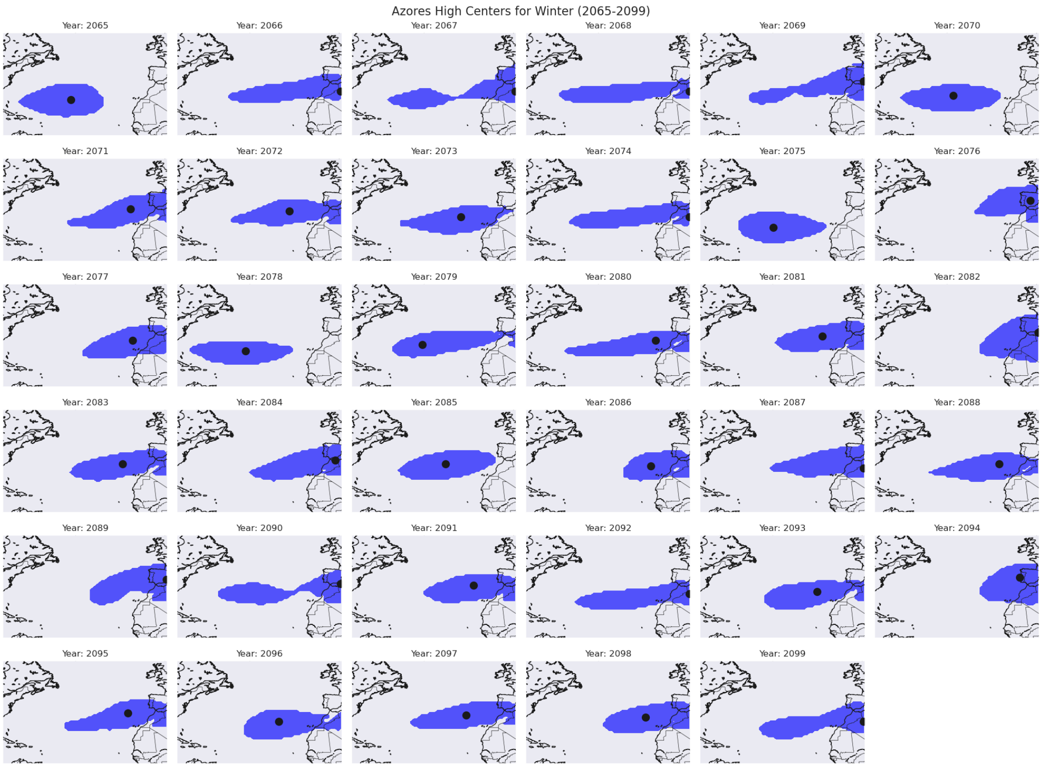

Figure B.1 Future projection Azores High Centers for Winter (2065-2099)

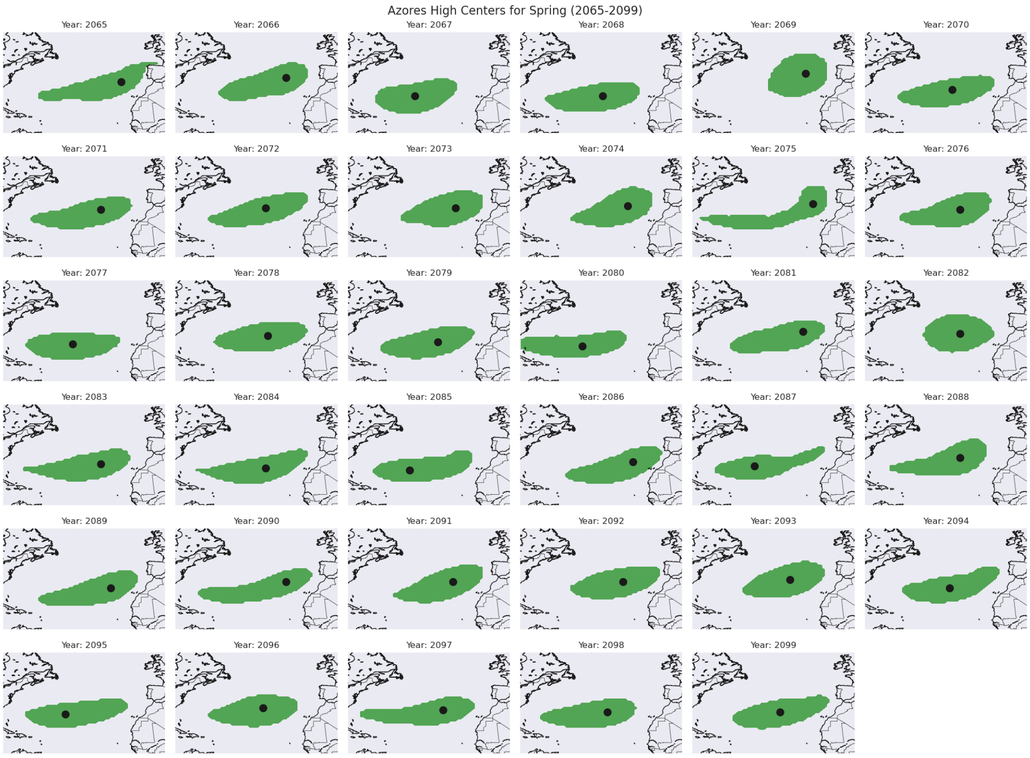

Figure B.2 Future projection Azores High Centers for Spring (2065-2099)

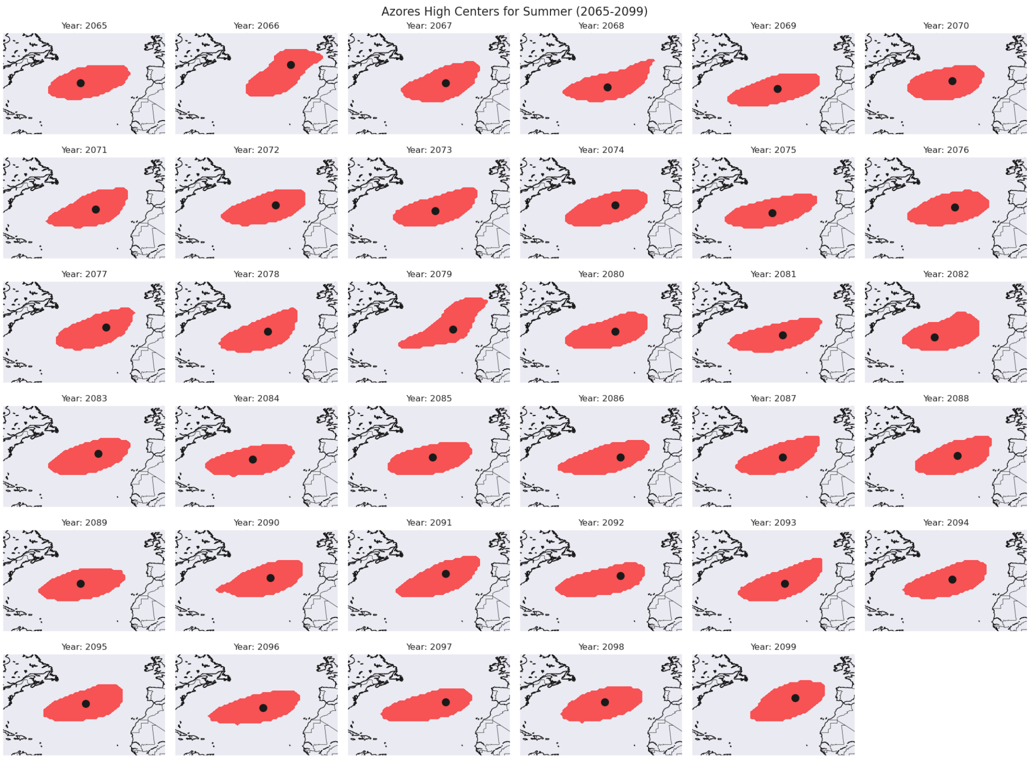

Figure B.3 Future projection Azores High Centers for Summer (2065-2099)

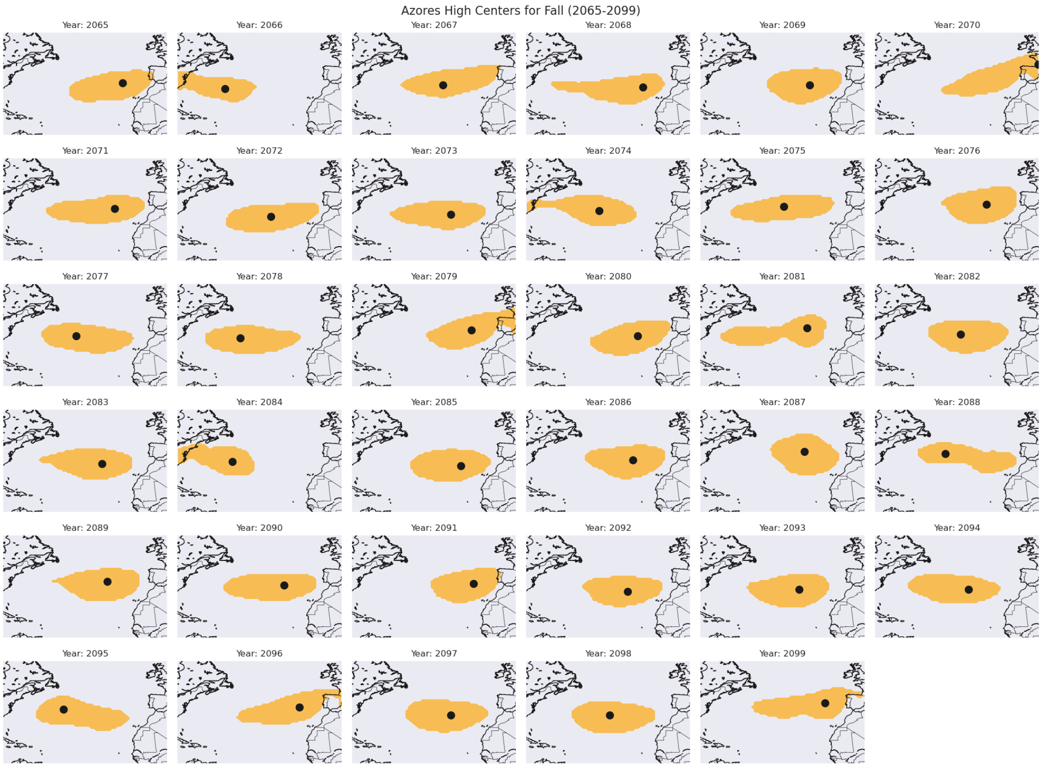

Figure B.4 Future projection Azores High Centers for Fall (2065-2099)