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CLIMATE CHANGE SCENARIOS IN THE AZORES AND MADEIRA ISLANDS

F. D. Santos
Department of Physics
University of Lisbon
Observatório Astronómico de Lisboa
Edifício Leste, Tapada da Ajuda
1349-018 Lisboa PORTUGAL

M. A. Valente, Pedro M. A. Miranda, Ana Aguiar
Centro de Geofísica and Department of Physics
University of Lisbon
Faculdade de Ciências, Campo Grande, Ed. C8
1749-016 Lisboa PORTUGAL

E. B. Azevedo
Departmento de Ciências Agrárias
University of the Azores
Campus de Angra, Terra-Chã
9701-851 Angra do Heroísmo, Açores PORTUGAL

A.R. Tomé
Department of Physics
University of Beira Interior, CGUL
Rua Marquês de Ávila e Bolama
6201-001 Covilhã PORTUGAL

F. Coelho
Instituto de Meteorologia
Rua C ao Aeroporto
1749-077 Lisboa PORTUGAL

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ABSTRACT

A simple parcel model (CIELO) has been used to downscale climate change scenarios for the 21st century, obtained with the HadCM3 GCM, in the Madeira and Azores Islands. The HadCM3 model has been run using the SRES emissions scenarios A2 and B2. CIELO is a relatively simple model, based on the transformations experienced by an air mass ascending a mountain, and simulates the evolution of an air parcel's physical properties starting from the sea level. There are two free parameters in CIELO regulating the precipitation processes, which have been adjusted initially to the Terceira Island (Azores), using observations. The same set of parameters was used in the S. Miguel Island (Azores). A different set of parameters was applied to Madeira, to take account of the different climate conditions. Preliminary results indicate larger climate changes in Madeira than in the Azores region, with the annual precipitation in Madeira decreasing up to 35% in the 2070-2099 period, when compared to the control period 1961-1990. In this scenario, Madeira Winters become drier, whereas in the Azores they turn wetter. Temperature anomalies are slightly higher in Madeira (less than +3ºC) than in the Azores (less than +2.3ºC).

1. INTRODUCTION

Island environments are known to be particularly sensitive to externally induced changes. The main reason for this sensitivity is the fact that many of the adaptation measures that may be thought, which involve relocation of resources and activities, cannot happen in the limited areas of most islands. On the other hand, islands are highly dependent on their coastal areas, and these have been identified as one of the major targets of climate change impacts (IPCC WGII TAR, 2001). In spite of the total area and population of small islands, they constitute very important assets for the countries they integrate, for many reasons, namely for their unique landscapes and climates, and for their strategic and economic advantages in the use of the ocean.

However, the analysis of climate change scenarios and impacts in small islands is rather difficult. Global Circulation models (GCMs), the main tool for the production of climate scenarios, cannot simulate the small scale topographic and coastal features of those islands, which are nevertheless responsible for most of the observed climate. So, one must design special methods to infer (downscale) the impacts of the enhanced greenhouse effect that, while consistent with established global scenarios, may account for the special nature of the island physiography.

In the present study, a new downscaling technique is developed and applied to the Azores and Madeira islands. The technique is tested against observed climatology, constituting, in that case, an alternative to non-physical interpolating techniques widely used. The quest to investigate the impact of future global warming due to greenhouse gases concentration increases on the climate of the Azores and Madeira is another aim of this paper. Climate scenarios for the 21st century, obtained from the HadCM3 Hadley Centre (UK) large scale climate model (Gordon *et al*., 2000), run with the A2 and B2 SRES emissions scenarios, are here downscaled to the islands of Terceira and S. Miguel, in the Azores, and to Madeira island, using a simple parcel model. The scenarios are constructed for the period 2070-2099, and are compared with the climate modeled in the control period 1961-1990. Anomalies between these two 30-year periods are analyzed in this work and the results give an indication of the impacts the future greenhouse gas concentration increase could have on the islands' ecosystems in the late 21st century.

Section 2 of this paper summarily describes the climate in the Azores and Madeira islands. In section 3, a brief review of the main methods used to downscale global scale climate model data is presented. Section 4 comprises a concise description of the CIELO model used here as the downscaling technique. In sections 5 and 6 the scenarios for the chosen islands in the Azores and Madeira are presented and analyzed. Finally, in section 7 the impacts on the islands' ecosystems are discussed and the main conclusions obtained in this work are emphasized.

2. THE ATLANTIC ISLANDS OF AZORES AND MADEIRA

The Azores archipelago is localized in the North Atlantic ridge, between the latitudes of 36º 45'N and 39º 43'N and the longitudes of 24º 45'W and 31º 17'W. It comprises 9 islands of volcanic origin distributed by 3 groups, West, Central (including Terceira) and East (including S. Miguel). The largest island is S. Miguel and the smallest Corvo (West group). Both Terceira and S. Miguel have active and extinct volcanoes that dominate the main topographic features, and the highest peaks reach altitudes of just over 1000m (see Fig. 1a,b). 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.

Madeira archipelago is composed of 2 main islands, Madeira (the largest one) and Porto Santo (positioned Northeast of Madeira). Madeira island is located at the latitude of the Northern African coast (32º 45'N of latitude and 17º 00'W of longitude) and its terrain is of volcanic origin, being characterized by very rugged orography with high peaks and deep ravines. The highest peaks have around 1800m of altitude (Fig. 1c). 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 stationary depressions can provoke extreme precipitation events.

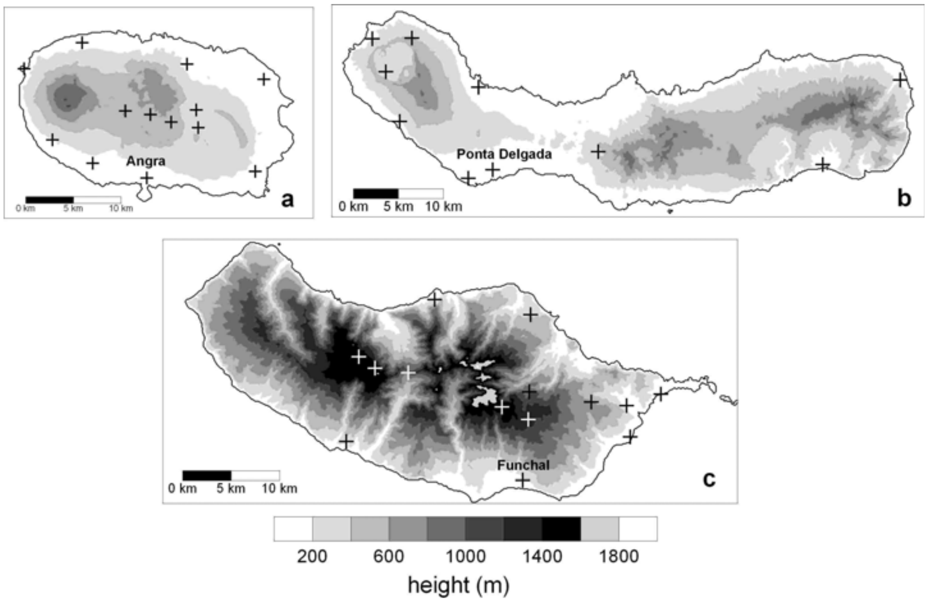

Figure 1 Topography and meteorological stations (crosses) in (a) Terceira; (b) S. Miguel; (c) Madeira.

Both Portuguese archipelagos have temperate climates, characterized by mild temperatures all year round, at low altitudes, and Azores has a rather wet climate. In each island of both archipelagos with human habitants (9 in the Azores and 2 in Madeira), the distribution of rain is highly controlled by topography, with very wet high ground and drier coastal areas. In fact, one of the main processes responsible for the production of precipitation in these islands is the ascent of moist air over the islands terrain. The mean annual precipitation observed during the period 1961-1990 in the 3 analyzed islands is shown in Fig. 2. Fig. 3 represents the mean maximum temperature in Summer (JJA) in the same period.

Observed minimum and maximum temperatures taken at several meteorological stations on these islands reveal that these atmospheric parameters have been increasing steadily during the last quarter of century (Fig. 4), in phase with the observed increase in the average global temperature (Karl et al., 2000). In

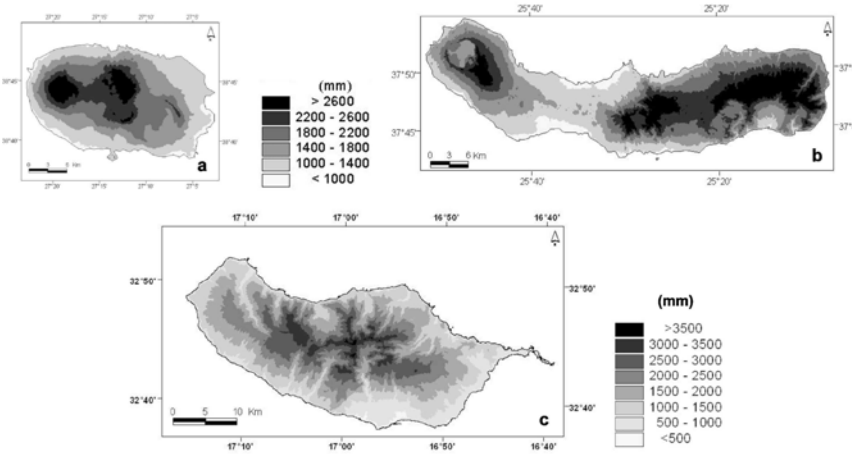

Figure 2 Annual precipitation in 1961-1990: (a) Terceira; (b) S.Miguel and (c) Madeira. Data supplied by the Portuguese Institute of Meteorology.

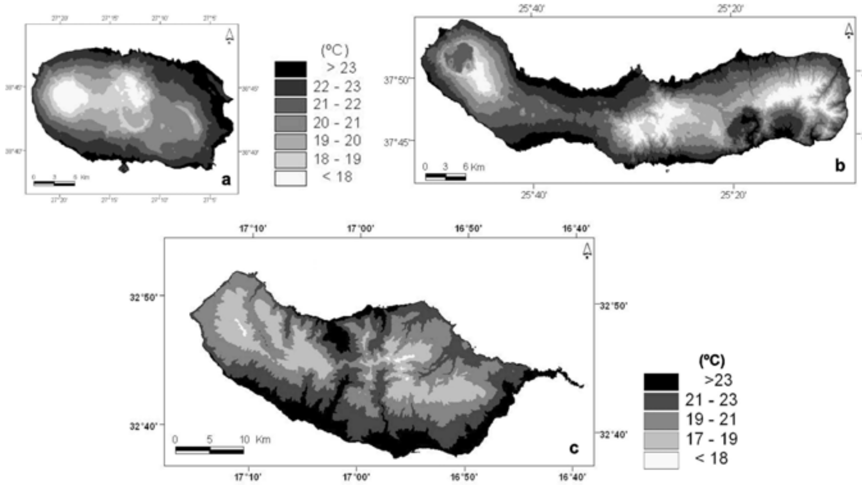

Figure 3 As Fig. 2 but for the mean Summer (JJA) maximum temperature in 1961-1990.

Fig. 4, superimposed to the temperature series are linear piecewise adjustments obtained calculating the breakpoints (years indicated) with the Tomé and Miranda (2004) methodology. Trends (in ºC/decade) are presented for the last segment adjusted to each series. In Angra (Terceira) maximum and minimum temperatures increased at a rate of 0.3ºC/decade since 1963 and 1974 respectively, whereas in Funchal (Madeira) temperatures are increasing at even faster rates (0.53ºC/decade for maximum temperature and 0.66ºC/decade for minimum temperature) since early 1970s.

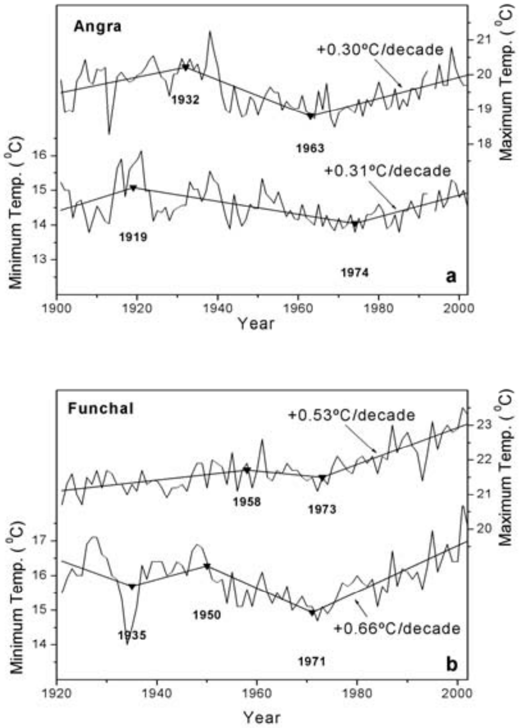

Figure 4 Temporal evolution of minimum (bottom curves) and maximum temperatures (top curves) in Angra (Terceira) and Funchal (Madeira).

3. DOWNSCALING OF GCM DATA

The construction of climate change scenarios usually starts from simulations with Global Circulation Models (GCMs), which are coupled ocean-atmosphere-soil-cryosphere models including interactions with biosphere, forced with greenhouse gases emissions scenarios for the forthcoming years. However, islands with horizontal scales of the order of tens of km, as is the case of the Azores and Madeira, are subscale orographic features for GCMs, as these models have horizontal scales of the order of hundreds of km. Therefore, the construction of climate change scenarios in these archipelagos requires the use of a downscaling technique to regionalize scenarios obtained at larger scales. The different regionalization methodologies commonly used to downscale GCM scenarios to smaller scales are divided in 3 main groups: variable and increased resolution atmospheric GCMs (AGCMs); regional climate models (RCMs); and statistical (empirical or dynamical) methods. The first two methodologies are eminently dynamical downscaling techniques.

Downscaling with variable and increased resolution GCMs is a recent technique that includes enhancing the AGCM spatial resolution (typically to 50km) in a particular region of the globe, or performing global high spatial (of the order of 100km) resolution AGCM simulations for short time slices. Examples of this technique include Gibelin and Dequé (2003), with the ARPEGE model with higher resolution in the Mediterranean basin, and Stratton (1999), using the increased resolution Hadley Centre global atmospheric model HadAM3. In this methodology, the AGCMs climate change simulations are forced at the lower boundary by a coupled GCM.

Regional Climate Models have a horizontal resolution of the order of tens of km (50km in many cases), cover a particular area (such as Europe and the Eastern Atlantic) and are forced at the boundaries by a GCM (or intermediately by a high resolution AGCM). The vast majority of RCMs are atmospheric-only models, although, with the increase in computational resources, coupled ocean-atmosphere RCMs are starting to be used in climate studies. Miranda *et al*. (2002) and Hulme *et al*. (2002) analized climate change scenarios for the end of the 21st century respectively in Portugal and the UK using the Hadley Centre RCMs HadRM2 and HadRM3, whereas Gallardo *et al*. (1999) constructed scenarios for the Iberian Peninsula with the PROMES model. In these studies, both HadRM2 and PROMES have been forced by the Hadley Centre’s GCM, HadCM2, whereas HadRM3 was forced by the latest Hadley Centre GCM HadCM3.

In statistical downscaling methods, regional or local climate information is derived from a statistical model relating large-scale local variables (“predictors”) to regional or local variables (“predictands”) (IPCC WGI TAR, 2001). These methods are computationally inexpensive and can be used to provide local information in climate change impacts studies. Empirical/statistical methods include weather generators (Wilks and Wilby, 1999), transfer function techniques such as artificial neural networks (Trigo and Palutikof, 1999) and also weather typing schemes (Conway *et al*., 1996). Weather typing can also be used in statistical dynamical downscaling (Frey-Buness *et al*., 1995), where weather regimes are simulated by RCMs. The major theoretical weakness of statistical downscaling methods is that they assume that the statistical relationships developed for present day climate are maintained under the different forcing conditions of possible future climates, an assumption that is not verifiable (IPCC WGI TAR, 2001).

The dynamical downscaling methodologies based on AGCM and RCM simulations are insufficient to obtain climate change scenarios in the Azores and Madeira islands, since the horizontal scales of these models are too coarse to give a detailed representation of the islands' topography. Statistical downscaling is more adequate to construct climate change scenarios in small limited regions. Sumner *et al*. (2003) analyzed precipitation changes due to climate warming in the Mediterranean Spanish coast, which included the Balearic Islands**.** This work was based on the classification of weather types and rain pattern types, which were defined from climatology. Changes in the frequency of weather types in simulations of the ECHAM model, performed with the IS92a "business as usual" emissions scenario (Leggett *et al*., 1992), allowed the authors to construct precipitation scenarios for the last 2 decades of the 21st century. For the Balearic Islands, the authors concluded that both Maiorca and Menorca could experience a small decrease in annual precipitation (less than 4%) in the period 2080-2099 when compared to present conditions, whereas in Ibiza a small increase (2-4%) is projected. However, the study also found a large degree of uncertainty in the predicted precipitation changes for the Balearic Islands.

In the present work, a different dynamical technique has been developed, which consists in simulating the precipitation and temperature variations suffered by an air mass as it ascends and descends an island's topography, starting from sea level. This technique, which may be classified as a statistical-dynamical method, is the basis of the CIELO model, described in the following section.

4. CIELO model

CIELO is a simple parcel model developed by Azevedo (1996) and Azevedo *et al.*, (1998, 1999). Conceptually, the processes modelled are as follows: initially a moist air column over the ocean, with temperature T_1 and relative humidity RH_1 is forced to ascend the upstream side of the island's topography in the wind direction; during the ascending path, the column's temperature decreases and the air saturates, with the consequent condensation of water vapor in the column; in favorable physical conditions (enough vertical motion during ascent and liquid water), the liquid water precipitates; on the lee side of the island, the air mass acquires a relative humidity $RH_2<RH_1$ and a temperature $T_2>T_1$, characteristic of the föhn effect. The described precipitation process modelled in CIELO is designated by orographic precipitation. The input variables in CIELO are the temperature, relative humidity, pressure, precipitation and wind intensity and direction, all taken at mean sea level. The model can use daily or monthly data, and in the latter case, the frequency of each wind direction is computed from daily data. In the monthly version, the model computes precipitation fields for each main wind direction (N, NE, E, SE, S, SW, W and NW) with mean wind speeds corresponding to the monthly average wind speed in the respective direction. The eight results (one for each main direction) are then linearly combined, weighted by the corresponding frequency in the data, to give the monthly temperature and precipitation results on the model horizontal grid covering the island.

The calibration of CIELO requires the adjustment of two parameters (α and β) that govern the efficiency of the precipitation processes. Initially the model was developed and calibrated for the Terceira island (Azevedo, 1996; Azevedo *et al*., 1999), and the parameters α and β chosen in those studies have been tried in the present work. Here the CIELO validation procedure for Terceira, using observational data, confirms that these values are adequate to simulate the precipitation field in this island. Furthermore the validation of the model in S. Miguel yields similar values for α and β. In Madeira, the particular distribution of the precipitation field required different values of α and β than the ones used in the Azores.

The island climate scenarios for the 21st century were obtained from the Hadley Centre (UK) GCM HadCM3 run with the greenhouse gas emissions scenarios A2 and B2. These are part of the SRES set of scenarios developed by the IPCC (IPCC WGI TAR, 2001) and have been lately widely used in climate impacts assessments for the 21st century (Parry, 2000; IPCC WGII TAR, 2001) The A2 scenario projects a CO_2 concentration of around 850 ppmv in 2100, whereas the B2 scenario levels at approximately 600 ppmv by the end of the 21st century. Both emissions scenarios start from a concentration of 350 ppmv in 1990. The present concentration of CO_2 is around 375 ppmv. The SRES emissions scenarios include aerosol effects. HadCM3 is a coupled atmosphere-ocean GCM that has a horizontal resolution of 3.75º of longitude by 2.5º of latitude and ranks among the GCMs with the highest resolution. This version of the Hadley Centre (UK) climate model does not require a flux correction to balance the climate drift and uses an individual forcing for each of the greenhouse gases, instead of an equivalent CO_2 forcing. The daily HadCM3 data used in this work has been supplied by the LINK network (Viner, 1996). Two 30-year periods (1961-1990) and (2070-2099) of the HadCM3 data have been chosen to force CIELO, with input data consisting of time series of minimum and maximum temperature, pressure, precipitation, relative humidity and wind extracted for the HadCM3 grid point nearest to each of the islands.

5. CLIMATE SCENARIOS IN THE AZORES

Terceira Island

To calibrate and validate the CIELO model in Terceira for the precipitation variable, a set of observations in 13 meteorological or udometric stations (see Fig. 1a) was used for the period 1980-1984. For Terceira, CIELO was forced by daily observations in Angra (on the island's South coast). A linear regression between the monthly mean observations in the 13 Terceira stations and the values of precipitation obtained with CIELO in the nearest grid points of these stations revealed high correlation values between both sets of precipitation, typically between 0.7 and 0.9. Moreover, the slope of the linear regression between model results and observations was found to be very close to 1 in almost every station, with the largest underestimation of precipitation being of the order of 25% in 2 stations. Taking into account that the 13 station observations were for 1980-1994 and the climate normals for 1961-1990, the similarities between the precipitation distribution given by CIELO and the climate normals also confirm the values of α and β used in Terceira as adequate for applying the downscaling procedure to the HadCM3 control and scenario sets of data. Fig. 5 presents the CIELO annual precipitation obtained with the control HADCM3 forcing. A stronger precipitation gradient between the coast and the highest regions is found in Fig. 5 than in Fig. 2a. This is due to a combination of larger values of wind speed and lower precipitation given by the HadCM3 control simulation in comparison with observations at Angra. In fact, the HadCM3 grid point chosen to force CIELO

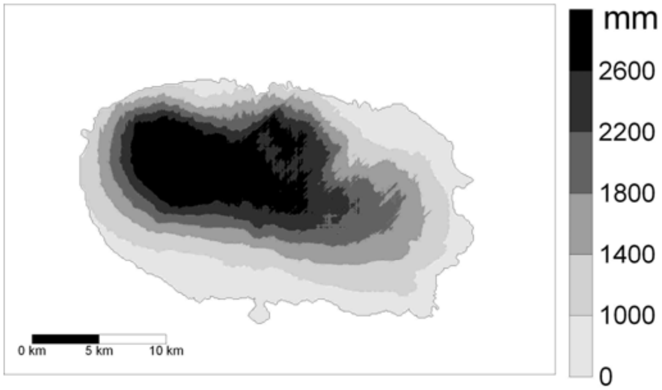

Figure 5 Mean annual precipitation obtained in Terceira with CIELO (input daily data - control simulation of HadCM3, 1961-1990).

is localized on the ocean, where the surface friction effect is much smaller than in land, which explains the higher wind speed values. The HadCM3 precipitation underestimation is compensated by the higher wind values in the orographic precipitation process modelled by CIELO, thus giving a mean annual precipitation distribution that is acceptable when compared to the climate normal (Fig. 2a).

When anomalies are computed between the scenarios (for 2070-2099) and the control CIELO simulations, we expect the forcing precipitation and wind bias to be reduced. The Winter and Summer precipitation anomalies for the A2 scenario (with the largest greenhouse gases emissions) are represented in Fig. 6. Precipitation anomalies in this work are presented as a percentage of the control simulation. Results obtained with scenario B2 are discussed but not shown, since the fields' spatial pattern is very similar to what was obtained for the A2 scenario.

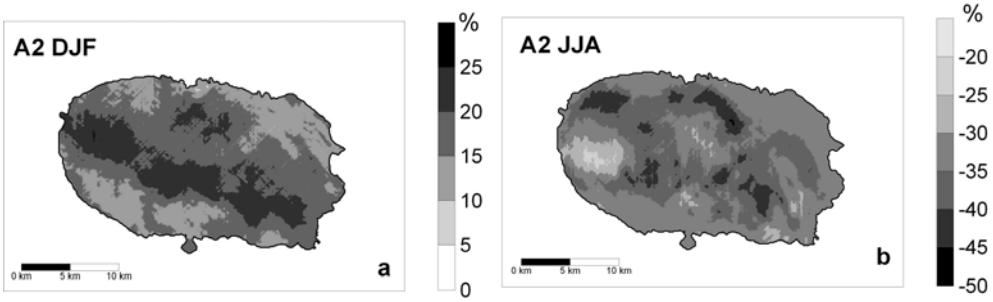

Figure 6 Precipitation anomalies given by CIELO (Terceira) forced by HadCM3 data, A2 scenario: (a) Winter; (b) Summer.

In Winter both scenarios project an increase in precipitation that is larger (between 10% and 25%) in the A2 scenario. The B2 scenario predicts an increase in the range 3%-22%. Summer precipitation suffers a substantial decrease in the A2 scenario (of approximately 25%-45%), and a more moderate decrease in the B2 scenario (of 20%-35%). During Spring and Fall in the period 2070-2099, both scenarios show a net decrease in precipitation, which, combined with the Winter increase, gives a small variation (less than 10%) in the annual Terceira precipitation (not shown). Negative annual anomalies cover the largest area (mainly in the South) of the island in scenario A2, the most severe, whereas in B2 positive anomalies are dominant.

Summer maximum temperature anomalies for scenario A2 are presented in Fig. 7. In this scenario the maximum temperature has an increase of 1.7-2.3ºC, whereas CIELO projects positive anomalies of 1.2-1.5ºC in scenario B2. The Southwest regions in Terceira are the ones experiencing the largest temperature increases in Summer. For the Winter minimum temperature, the increases are

+1.9ºC in A2 and +1ºC in B2 (not shown) being approximately constant on the whole island.

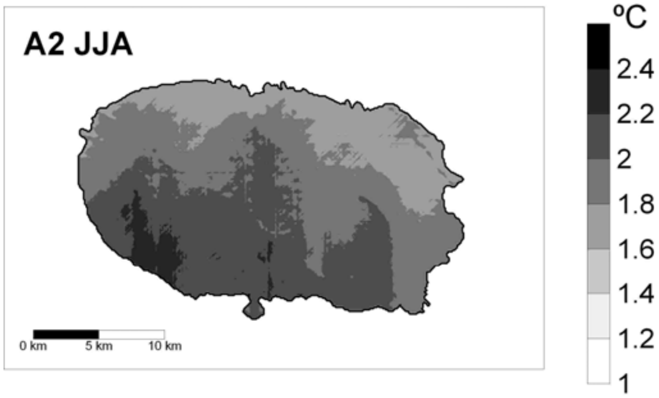

Figure 7 Anomalies of Terceira maximum temperature in Summer, A2 scenario.

The temperature increases simulated for Terceira are quite small in comparison to those projected for continental regions at the same latitude (IPCC WGI TAR, 2001). The moderating influence of the ocean seems to shield the island from more drastic temperature increases in the late 21st century. However the increase in Winter precipitation can have a significant impact on the island, leading to the occurrence of more extreme precipitation events than at present. Also the Spring and Fall precipitation decrease can affect the development of crops and local flora. The future climate of Terceira modelled by CIELO, used as a downscaling tool for the HadCM3 scenarios, could thus be warmer by 1-2ºC than the present climate and have a shorter rainy season, more concentrated on the Winter months.

S. Miguel Island

For S. Miguel, the CIELO validation procedure led to the conclusion that the best correlations and slope of linear regressions between observations and modeled values were obtained using monthly input data. Ten sets of observational data for the period 1973-1994 (from stations marked in fig. 1b) were used to validate the model.

The CIELO A2 and B2 scenario simulations are essentially similar to the ones obtained for Terceira. Precipitation anomalies between the A2 scenario and control run are presented in Figure 8.

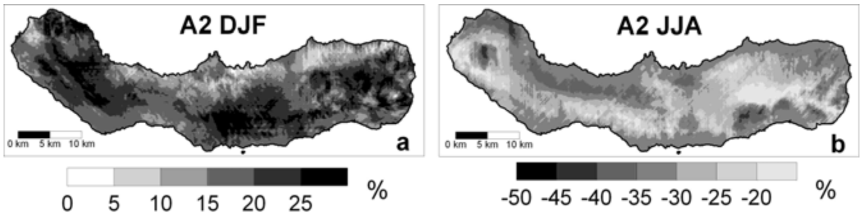

Figure 8 Precipitation anomalies given by CIELO (S. Miguel) forced by monthly HadCM3 data, A2 scenario: (a) Winter; (b) Summer.

The Winter season becomes wetter in 2070-2099 by 5%-25% in scenario A2 and by 0-25% in scenario B2. Simulated Summers are considerably drier in the future period by 20%-40% in A2 and between 10%-25% in B2. As in Terceira, the annual precipitation in the future period is somewhat similar to the control precipitation, with anomalies being in the range ±10%. In scenario A2 the annual precipitation anomalies are predominantly negative, while in the B2 scenario anomalies are mainly positive throughout S. Miguel.

The A2 Summer maximum temperature anomalies (Fig. 9 for the A2 scenario) have the same range of spatial variation that was found for Terceira. In scenario A2 this range is 1.7-2.3ºC, and in scenario B2, 1.2-1.5ºC.

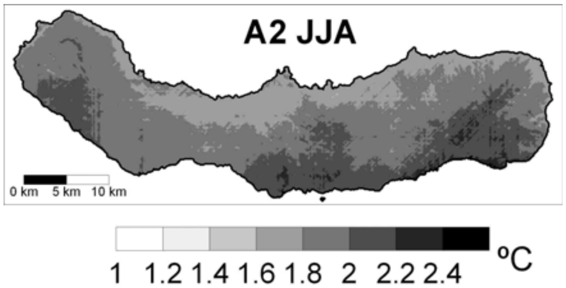

Figure 9 Summer maximum temperature anomalies in S. Miguel (scenario A2).

6. CLIMATE SCENARIOS IN MADEIRA ISLAND

For the calibration and validation of CIELO in Madeira, a set of precipitation observations in 14 meteorological stations was used for the period 1980-1994 (see Fig. 1c). Monthly data from Porto Santo (at almost sea level) was chosen as the input data to force CIELO. The calibration procedure (determination of the best α and β) was based on the minimization of the squared deviations between the precipitation observations and the modelled values. A smoothed orography obtained with a 15-point moving average was used instead of the original grid. The correlations and slopes of linear regressions between observations and simulations were on average 0.77 and 0.88 respectively.

The CIELO annual precipitation obtained with the HadCM3 control simulation (input data from a HadCM3 grid point near Porto Santo) is shown in Fig. 10. Both maps in Fig. 10 and 2c (1961-1990 climatology) present a marked North-South asymmetry in the precipitation distribution. The Northern of Madeira appears wetter than the South in the CIELO simulations, due to the predominance of Northerly winds in the HadCM3 results during the year and especially during Spring to Fall. The capability of CIELO in reproducing the observed precipitation asymmetry pattern in Madeira is remarkable.

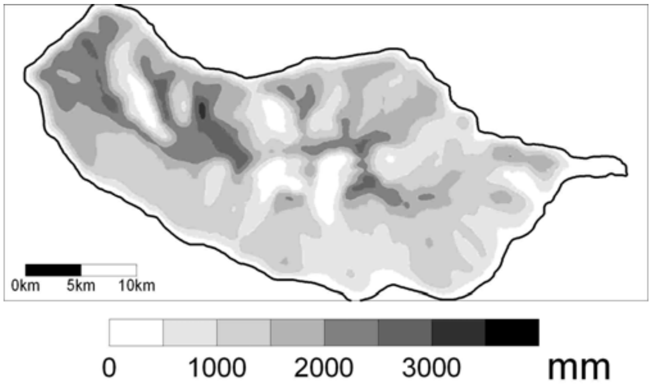

Figure 10 Mean annual precipitation obtained with CIELO in Madeira (input monthly data - control simulation of HadCM3 - 1961-1990).

Winter and Summer precipitation anomalies between A2 HadCM3 scenarios and control results are shown in Fig. 11. Winter precipitation decreases in the future scenarios (by 15%-35% in A2 and by 20%-40% in B2) whereas Summer precipitation suffers a substantial increase, particularly in the A2 scenario (20%-100%). In Winter the largest decreases are found in the Northern part of the island. During this season the predominant wind direction is from the SW quadrant and the greatest relative decreases occur downstream of the island’s peaks. On the other hand, in Summer the largest increases occur in the Northern side, being the wind essentially from the North quadrant during this season.

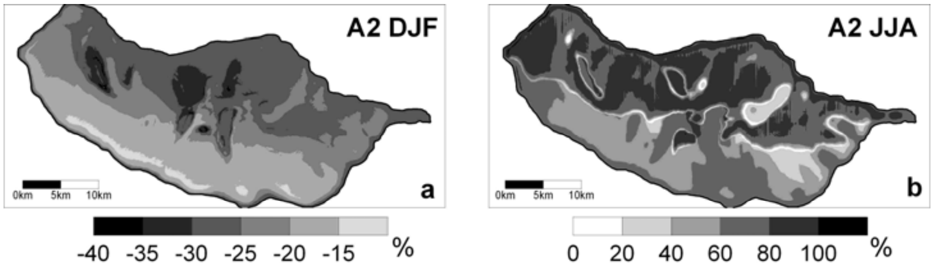

Figure 11 Precipitation anomalies in Madeira given by CIELO forced by HadCM3 data, A2 scenario: (a) Winter; (b) Summer.

Spring and Fall seasons in Madeira are also drier in 2070-2099 than in the control period, but the largest decreases of precipitation occur in these seasons in the Southern part of the island. The same pattern of precipitation anomalies is found in the annual maps (Fig. 12 for the A2 scenario). In both A2 and B2 scenarios, the loss of annual precipitation is very similar, varying between 20% and 35%. The increase of greenhouse gases concentration in the future scenarios has therefore a greater impact on precipitation in Madeira than in the Azores. Analyzing the distribution of absolute annual precipitation anomalies in Madeira (not shown), it is found that the highest regions, with larger precipitation values, are the ones that suffer the greatest future losses reaching up to 900mm/year. Since these regions are the main gathering water reservoirs in Madeira, a heavy fall in the water supply in the highest zones, coupled with losses throughout the island during the rainy season, leaves the island more vulnerable to episodes of drought by the end of the 21st century, with the subsequent impacts on water resources and on the local flora and agriculture.

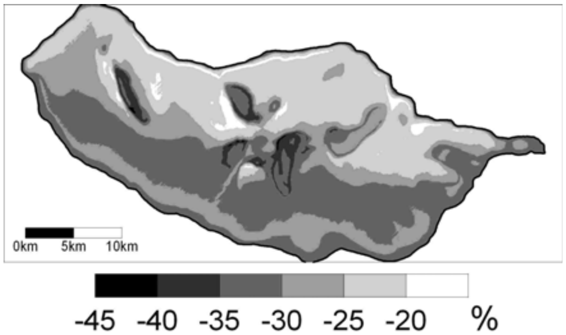

Figure 12 Annual precipitation anomalies in Madeira between 2070-2099 (scenario A2) and the control period.

Summer maximum temperature anomalies for the A2 scenario are presented in Fig. 13. This scenario has positive anomalies ranging from 2.4-3ºC and the B2 scenario shows a maximum temperature increase between 1.6 and 2.2ºC. These maximum temperature increases are approximately 1ºC higher than those found in the Azores. The largest anomalies are located, as in the Azores, near the South coast of the island, the downstream region that is affected by the Föhn effect due to the North Summer wind. Projected Winter minimum temperatures (not shown) suffer increases of the order of 2.6 to.2.9ºC in the A2 scenario and 1.5-1.8ºC in B2, with the largest anomalies occurring in the highest regions.

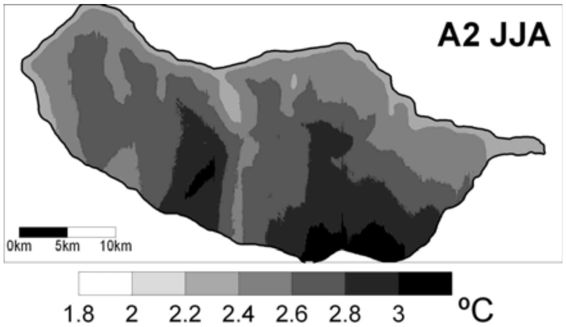

Figure 13 Summer maximum temperature anomalies in Madeira (scenario A2).

By the end of 21st century Madeira climate is thus projected to become hotter and drier, with much less Winter precipitation. Negative impacts should come mainly from the loss of annual precipitation, imposing serious water stresses on the island's hydrological resources.

7. DISCUSSION AND CONCLUSIONS

The Azores are located in the middle of North Atlantic. The archipelago has a population of around 240 000 people, distributed by the 9 islands. The most populated is S. Miguel (130 000 inhabitants), where the capital, Ponta Delgada, is located and Terceira is the second most populated island (60 000). As the North Atlantic has very few islands between North America and Europe, the Azores are used as an air stop both by civil and military aviation. For the same reason, maritime North Atlantic traffic also uses the Azores' ports frequently. The archipelago has a very characteristic natural beauty, due to its combination of humid, temperate climate and volcanic shaped physiography. However the Azores still suffer from some insularity isolation in relation to mainland Portugal, but the region has a large potential for tourism, as well as important agricultural (ex. cattle, milk) and fisheries resources. The tertiary sector is also expanding at a fast rate in the most populated islands. Climate change studies in the Azores are therefore of the utmost importance, since the island's economy depends in a large part on its natural resources. The present work indicates a small increase in temperature in the region due to projected increases in greenhouse gases concentration for the end of the 21st century. The moderating effect of the ocean on the temperature field shields the islands from more drastic temperature increases such as the ones projected for mainland Portugal (Miranda *et al*, 2002). The greatest estimated impact of global warming may be the change in annual precipitation distribution, with wetter Winters and the other seasons becoming drier. This could have a significant impact on the islands' water resources, increasing the severe precipitation events in Winter and imposing water deficit stresses in Summer. Landslides are a frequent catastrophic event in the Azores, and the increased Winter precipitation could aggravate this problem in the future.

The impacts on Madeira island, with a population of around 250 000 inhabitants in 740 km^2, are likely to be even more significant. First, the projected changes in temperature are higher, closer to the world average. More importantly, the changes in precipitation correspond to a significant annual loss of water (of the order of 1/3 of current values) and to a change in the annual cycle that is the opposite of what is projected to the Azores, leading to an even larger reduction in Winter precipitation. Madeira is a region highly dependent on tourism, and has several natural ecosystems that may be threatened by a drier climate, namely a large area of protected humid forest. Also, the Madeira water resources depend mostly on the capturing of precipitation in the high grounds, which feeds into many small rivers and ground water systems. Hydroelectricity is also an important resource, fed by small reservoirs with large falls. All these systems require a lot of rain in the mountains. Current GCM data seems to indicate that some of that rain may fail in the future.

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