

FUTURE CLIMATE CHANGE OF THE SUBTROPICAL NORTH ATLANTIC: IMPLICATIONS FOR THE CLOUD FORESTS OF TENERIFE

FRANK N. SPERLING^{1*}, RICHARD WASHINGTON² and
ROBERT J. WHITTAKER²

¹*Environmental Change Institute, University of Oxford, 5 South Parks Road, Oxford OX1 3UB, U.K.*

²*School of Geography and the Environment, University of Oxford, Mansfield Road, Oxford,
OX1 3TB, U.K.*

E-mail: {Richard.Washington; Robert.Whittaker}@geog.ox.ac.uk

Abstract. This paper is concerned with climate change in the region of the Canary Islands and the potential implications for the laurel forests of Tenerife. Frequent orographic cloud formation during the dry season is of vital importance to the altitudinal distribution of the laurel forests, because it maintains a semi-humid environment in the otherwise semi-arid climate of the Canary Islands. The distinctive environmental conditions in conjunction with the location of the Canary Islands on the Northern poleward edge of the Hadley Circulation make these ecosystems potentially highly sensitive to regional changes in climatic conditions. To explore this sensitivity, we first quantify observed trends in humidity and temperature across an altitudinal transect at the base of the Anaga peninsular, and second, analyse the results of three GCM experiments (CGCM1, ECHAM4 and CSIRO) to develop alternative climate change scenarios, and third, use these data to assess likely shifts in the elevational distribution of the laurel forest climate envelope. We report a significant increase in relative humidity and decreases in the diurnal temperature range on Tenerife at altitudes below the trade wind inversion within the last 30 years during the dry season, which suggests an increased occurrence of low-level clouds. There is also partial evidence for a drying trend across the trade wind inversion, which may be linked to an increased subsidence. Overall, the models suggest a downward shift of the area climatically suitable for laurel forests, which may be driven by changes in temperature and moisture supply in the region as well as by larger-scale changes in the atmospheric circulation. Our findings contrast with previously published findings for a tropical montane cloud region, which predict an upward shift of the cloud base. This suggests, following the assumptions inherent in the models applied, that the ecological consequences of climate change for cloud forests may be linked to their relative location in the Hadley Circulation.

1. Introduction

The role of humans in inducing climate change has been asserted in four successive reports of the Intergovernmental Panel on Climate Change (IPCC, 1990, 1992, 1996, 2001). While the resultant warming is expected to be greatest in the Northern Hemisphere high latitude continental regions, marked changes are also anticipated

* Address for correspondence: Climate Change Team (ENV), 3140 O Street NW, Washington, D.C., 20007, U.S.A., E-mail: fsperling@gmx.de



Climatic Change **65**: 103–123, 2004.

© 2004 Kluwer Academic Publishers. Printed in the Netherlands.

in regions located sensitively with respect to transitions between different parts of the planetary circulation.

The Canary Islands ($27^{\circ}37'$ to $29^{\circ}27'$ N; $13^{\circ}20'$ to $18^{\circ}20'$ W) off the hyper-arid coast of Northwest Africa, are positioned astride the subtropical high-pressure belt, at the poleward limits of the Hadley Cell (Fernandopulle, 1976). Situated as they are in the eastern subtropical north Atlantic, their seasonal climate is largely driven by the location of the Azores anticyclone. Whereas Fuerteventura and Lanzarote, the easternmost islands of the Canaries, exhibit a desert-like climate and vegetation, the western islands of Gran Canaria, Tenerife, El Hierro, La Gomera and La Palma experience a Mediterranean-type climate of hot, dry summers and wet, warm winters. The mountains on these islands act as a topographical barrier to low-level, moist trade winds, creating a toposequence of contrasting climatic conditions. The result is a striking altitudinal zonation of vegetation, strongly differentiated between the windward and leeward sides of the islands (Fernández-Palacios and de Nicolás, 1995).

The altitudinal zonation is particularly marked on Tenerife, the largest and highest of the Canary Islands (Carlquist, 1974; Höllermann, 1981; Fernández-Palacios and de Nicolás, 1995). Due to the position of this roughly triangular-shaped island relative to the direction of the trades and the North Atlantic weather systems, two distinct slope types can be identified: a windward N slope and the leeward SE–SW slope. In general, altitude and exposure represent the major determinants of the observed altitudinal vegetation patterns, since temperature, moisture supply and radiation are connected to these variables (Fernández-Palacios and de Nicolás, 1995).

The laurel forest belt is altitudinally closely associated with the zone of orographic cloud formation, hence these ecosystems are also known as cloud forests. Tradewinds blowing over the ocean surface are forced to ascend as they encounter the formidable topographic barrier of the 3718 m high volcano Pico del Teide and the Anaga mountain range (maximum elevation: 1024 m). Orographically induced adiabatic cooling leads to the daily development of a cloud belt, locally referred to as 'mar des nubes' (sea of clouds), on the windward slope of the island during the otherwise dry summer months (e.g., Kämmer, 1974; de Nicolás et al., 1989; Fernández-Palacios and de Nicolás, 1995). The upper limit of the cloud layer is determined by the thermodynamic stability in the form of a well-developed tradewind inversion. The dry season cloud cover is of vital importance to the laurel forests, because it creates a semi-humid environment, which allows these ecosystems to persist in the otherwise semi-arid climate of the Canary Islands (López-Gómez and López-Gómez, 1979; Höllermann, 1981). This potentially makes these ecosystems particularly sensitive to climatic changes that influence the elevation and frequency of formation of the cloud belt.

Recent research by Still et al. (1999) and Pounds et al. (1999) suggests that climate change may pose a significant threat to tropical montane cloud forests (TMCFs), the tropical counterpart of the sub-tropical cloud forests. As horizontal

precipitation – the deposition of water droplets onto vegetation and soil surfaces through direct contact with clouds – often represents a crucial or the only water input for cloud forests during the dry season, it is of significant ecological importance to their biology. Still et al. (1999) used relative humidity (RH) as a proxy for cloud formation, and compared a $2 \times \text{CO}_2$ equilibrium scenario with a control simulation of present conditions derived from simulation runs of the GENESIS version-2 global climate model (Thompson and Pollard, 1997). They interpreted their findings as supporting an upward shift of the dry season cloud base. Their argument is further strengthened by the analysis of long-term climatic and demographic species data, which suggests that the decline in anuran populations in the cloud forests may be linked to reduction in the mist frequency since the mid-1970s (Pounds et al., 1999). Such a shift in the cloud base would threaten the existence, in their present form, of some of these biodiverse mountain ecosystems (Still et al., 1999).

The impact of climate change on cloud forest ecosystems may also be compounded by regional climatic forcing resulting from land-use change (Lawton et al., 2001). Model outputs suggest that deforestation can decrease the atmospheric moisture transfer to the mountain slopes, shifting the lifting condensation level and thus the cloud base upwards. Lawton et al. (2001) conclude that the effects will be dependent on location, such that near-coastal cloud forests are unlikely to be greatly affected, not initially having a substantial area of forest down slope and windward of them. This situation likely applies also to the laurel forests of Macaronesia (the Azores, Madeira and Canary and Cape Verde Islands), and especially to the drier islands like Tenerife, where the coastal zones are not wooded.

The present study represents the first attempt to model the potential consequences of climate change for the vertical distribution of clouds and thus for the vegetation zonation within Macaronesia; specifically focused on the laurel forests of Tenerife. We examine observed temperature and humidity data for a transect across the Anaga peninsular of Tenerife to establish temporal trends in these two key climatic variables. Then we compare these observed trends with projected trends in climatic parameters derived from three GCMs (CGCM1, CSIRO, ECHAM4) run in climate change mode (in each case using the IS92a emissions scenario) in the subtropical North Atlantic. We focus on the laurel forests, which occupy a climatically distinct envelope, and which represent biologically distinct and important ecosystems. Our analyses are limited to the dry season months of June, July and August (JJA), when persistent cloud cover is of vital importance to the laurel forests.

2. Study Area: Climate and Biological Importance of Laurel Forests

The laurel forests found on the mountainous islands of Macaronesia represent the remaining relicts of a Neogene oak-laurel community, which was well developed

in the circum-Mediterranean region about 20 million years ago (e.g., Bramwell, 1976; Höllermann, 1981; Morales et al., 1996). The climate of the Neogene was characterized by summer precipitation (Höllermann, 1981), which is in strong contrast to the dry season experienced at present on the Canary Islands and further illustrates the moisture requirements of the ecosystem during summer. As a result of increases in aridity and sinking temperatures since the Neogene, laurel forests became confined to coastal and mountainous areas with sufficient moisture (Höllermann, 1981). The islands of Macaronesia provided the necessary environmental conditions for the survival of the subtropical laurel forests since the climatic oscillations of the Pleistocene were buffered in part by the oceanic environment (Bramwell and Bramwell, 1974; Höllermann, 1981). Thus, the laurel forest found in Macaronesia represents the remaining fragment of a formerly widely distributed Tethyan-Tertiary flora, which is in a delicate balance with present climatic conditions.

Following their colonization in the late Tertiary, the distinctive environmental conditions created through the persistent cloud cover allowed these ecosystems to survive on these islands by creating a distinct semi-humid climate in a region where normally a semi-arid climate persists. On Tenerife, the surviving cloud forests are predominantly distributed in the North on the windward slopes of the Anaga mountain range, the windward slopes extending towards Teno (NW corner of the island) and towards the Las Cañadas plateau and Mt Teide, and to a lesser extent in the mountainous areas around Teno in the Southwest of the island.

The laurel forests communities located on top of the Anaga range of Tenerife receive frequent and considerable water input through clouds flowing over mountain ridges (Kämmer, 1974). Although in comparison with most tropical montane cloud forest ecosystems (Still et al., 1999), horizontal precipitation represents a relatively small source of total additional water input to laurel forests, it is thought to be of considerable importance during the dry season (Kämmer, 1974). Höllermann (1981) suggests that the reduction of the incoming solar radiation in fact plays a much more important ecological role. In conjunction with the high relative humidity (mean annual RH values have been estimated as 75–81% for laurel forests of Tenerife by Höllermann (1981); and 87–89% for Tenerife's Anaga laurel forest by Eguchi et al. (1999)), it leads to a reduction in evaporation and in the diurnal temperature range. In general, the trade wind inversion is located around 1500 m a.s.l., and clouds develop between 750 m and 1500 m (Huetz de Lempes, 1969). The cloud belt is most persistent during the dry summer months when the tradewind inversion, due to the dominating influence of the Azores anticyclone, is more stable than in winter (Fernandopulle, 1976). In summer, the lower humid layer is shallowest, confining the upper limit of the clouds most frequently to elevations between 1000 m and 1500 m (Kämmer, 1974).

The laurel forests are of outstanding biological and hydrological value to the Canary Islands. The Canarian flora is comprised of approximately 2000 species, 500 of which are endemics (Bramwell, 1990). A substantial proportion of the

endemic species, including many palaeoendemics, are found in the cloud forest belt (Bramwell, 1976). Of the forty most characteristic plant species found in the cloud forest belt, 75% are Canarian or Macaronesian endemics. All the dominant trees of the laurel forests at species or subspecies level are unique to the islands of Macaronesia (Bramwell, 1990). In addition, the laurel forest provides habitat for much of the Canarian endemic avifauna (Ballacado, 1976; Höllermann, 1978). Laurel forests also play an important role in watershed protection and erosion control (Melville, 1979; Höllermann, 1981). Höllermann (1981) points out that the region of the cloud forest belt represents the main region of water surplus, and that the laurel forest is essential for the infiltration and conservation of water, which would otherwise be lost due to run-off in winter or evaporation in summer. These ecosystem services provided directly or indirectly by cloud forests are of considerable socioeconomic importance in the context of an island group characterized by growing demands for water from agriculture and tourism (Melville, 1979; Bramwell, 1990; Fernández-Palacios and Martín Esquivel, 2001).

As in tropical montane cloud forests, it can be anticipated that changes in the distribution of the cloud belt as a result of climate change could have a significant impact on the ecology of the laurel zone, with further consequences for the hydrology of the region.

3. Data and Methodology

Climatic data were obtained from the Centro Meteorológico Territorial de Canarias Occidentales, Canary Islands, Spain, for a series of stations on an altitudinal transect across the windward and leeward slopes in the northwest of Tenerife. These include Santa Cruz de Tenerife at sea level on the leeward side (36 m a.s.l., 28°27'18" N, 16°14'56" W); Puerto de la Cruz (120 m, 28°24'06" N, 16°31'30" W); Valle Guerra Isamar (295 m, 28°30'14" N, 16°22'30" W) and Tacaronte (327 m, 28°29'11" N, 16°24'33" W) on the windward side, and La Laguna (Aeropuerto Norte) located on a saddle between the leeward and windward sides of the island (617 m, 28°28'10" N, 16°19'04" W). Long-term data were available for Izaña above the tradewind inversion (2367 m, 28°17'55" N, 16°29'25" W). Based on daily records for temperature, relative humidity and the diurnal temperature range, the JJA seasonal averages were calculated and examined for trends. The findings were then compared with simulations of the future climate for the region.

Simulated changes in future climates were obtained from three climate model experiments (CGCM1, ECHAM4 and the CSIRO models) run in transient mode using gaseous composition changes from the ISP92a greenhouse gas emissions scenario (Leggett et al., 1992). The scenario projects a doubling of CO₂ concentrations and a corresponding warming of the global average temperature by about 2 °C by the end of the 21st century with respect to 1990 levels, hereafter referred to as present conditions.

CGCM1 is the first version of the Canadian Global Coupled Model of the Canadian Centre for Climate Modelling and Analysis (Flato et al., 2000). CGCM1 has a resolution of T32 (approximately 3.7° longitude and 3.7° latitude) with 10 vertical levels in the atmosphere and about 1.8° longitude and 1.8° latitude in the ocean model (for further details see: 1992; Flato et al., 2000). Data from 1000, 850 and 500 hPa pressure levels were available for analysis.

ECHAM4 represents the fourth-generation atmospheric general circulation model developed by the Max Planck Institute for Meteorology (Roeckner et al., 1996). We used an ECHAM4 model run with spectral resolution of T42, which corresponds with a latitude/longitude resolution of about 2.8° . The atmospheric model is resolved into 19 layers and is coupled to an ocean general circulation model (OPYC, Oberhuber, 1993). The pressure levels analyzed were 1000, 900, 850, 700, 600 and 500 hPa.

The CSIRO coupled model was developed by the Commonwealth Scientific and Research Organization, Australia, and has been described by Gordon and O'Farrel (1997). The resolution of the atmospheric model is set at 3.2° latitude by 5.6° longitude and the atmosphere is represented as nine vertical levels. Climatic variables could be obtained at the following pressure levels: 982.19, 919.9, 807.3, 661.9 and 500 hPa. The pressure of 982.19 hPa was taken as being indicative of near surface trends comparable to the 1000 hPa pressure levels of CGCM1 and ECHAM4. The ocean model is a grid point model, which consists of 21 layers and is based on the GFDL ocean model of Bryan (1969) and Cox (1984).

Climate models are the only plausible means of estimating future climates. For studies concerned with mesoscale climate features, such as topographically-generated stratiform cloud in the trade winds (of concern in this paper), resolution and therefore the scale at which physical process are represented in the models becomes problematic. Such cloud formation occurs at scales much finer than the resolution of the GCMs. A computationally expensive way to deal with this problem is to run local area models at resolutions capable of resolving the processes of interest (e.g., Parry and Carter, 1998; Lawton et al., 2001). Another approach is to parameterize the process of interest: for instance, cloud cover may be estimated by using relative humidity as a proxy (e.g., Parry and Carter, 1998; Still et al., 1999). In this study we adopt the latter approach.

Temperature and specific humidity data were extracted from each of the GCMs for the grid box corresponding most closely with the location of the islands. The average lifting condensation level (LCL; the average altitude of cloud formation) for the JJA dry season was estimated from the dew point depression. The mean JJA LCL values estimated for 2061–2090 were compared to the 1961–1990 value; the latter period being generally recognized as the standard present climatic baseline. As microclimatic effects cannot be taken into account, we are concerned mainly with relative shifts in the cloud layer and the ecological implications of this. In addition, time trends in relative humidity were compared with values at higher

altitudes in each model, since the decrease in relative humidity across the tradewind inversion can serve as a measure of inversion intensity (Hastenrath, 1991).

Trends in the time series were determined by linear regression analysis. Since the simulation length and the data available from the model runs vary, trends were analyzed for general comparison from 1960 to 2099, which serves as the reference period (as it represents the maximum data length available from the CSIRO experiment). Furthermore, the statistical analyses were extended to the longer, entire data records available for CGCM1 (1900 to 2100) and ECHAM4 (1860 to 2099). Differences between the 30-year means in the climate simulations were tested for their significance using the two-tailed Student's *t*-test for independent samples (McGuffie and Henderson-Sellers, 1997). Trends and changes were considered statistically significant where $p \leq 0.05$. This test establishes probability of the difference in the means of two samples having occurred by chance.

4. Results

The JJA observed mean temperature data for Tenerife show a significant warming trend over the last thirty years. There has been a $0.16^\circ\text{C}/\text{decade}$ warming trend ($p = 0.029$) from 1950 to 1999 at Izaña (2367 m a.s.l., Figure 1a), within which the 1970 to 1999 period saw a rise of $0.45^\circ\text{C}/\text{decade}$. The JJA mean at the mid-elevation station of Aeropuerto de Los Rodeos Norte at La Laguna (650 m a.s.l., windward slope) shows a significant increase from 1972 to 1999 ($p = 0.005$; Figure 1b). While no significant change in temperature occurred at Santa Cruz (36 m a.s.l.) for the entire continuous recording period from 1925 to 1999, a warming trend can be detected during the last 30 ($p = 0.003$) and 40 years ($p = 0.03$) (Figure 1c). These findings suggest that a shift to a new temperature regime has taken place during the last few decades.

The only continuous record we have for relative humidity below the tradewind inversion was for Santa Cruz (Figure 2). These data show a significant upward trend for the last 30 years ($p = 0.006$) as well as for the entire measurement period from 1931 to 1999 ($p < 0.001$), for which there is an increase of JJA average relative humidity of about 1.1% per decade. No significant trend in relative humidity can be detected above the tradewind inversion at Izaña during the past 30 years or for the entire period of observations from 1950 to 1999.

An increase in low level cloud cover and moisture in the atmosphere would result in more solar radiation being reflected to space during the day while trapping more thermal infrared radiation emitted from the surface during the night. This scenario is supported by the analysis of the diurnal temperature range (Figures 3a,b). For all five locations situated below the altitude of the tradewind inversion, a significant decrease in the diurnal temperature range can be observed ($p < 0.005$), while the relative humidity data from Santa Cruz suggest a significant increase in relative humidity ($p < 0.05$). The decrease in diurnal temperature range is most

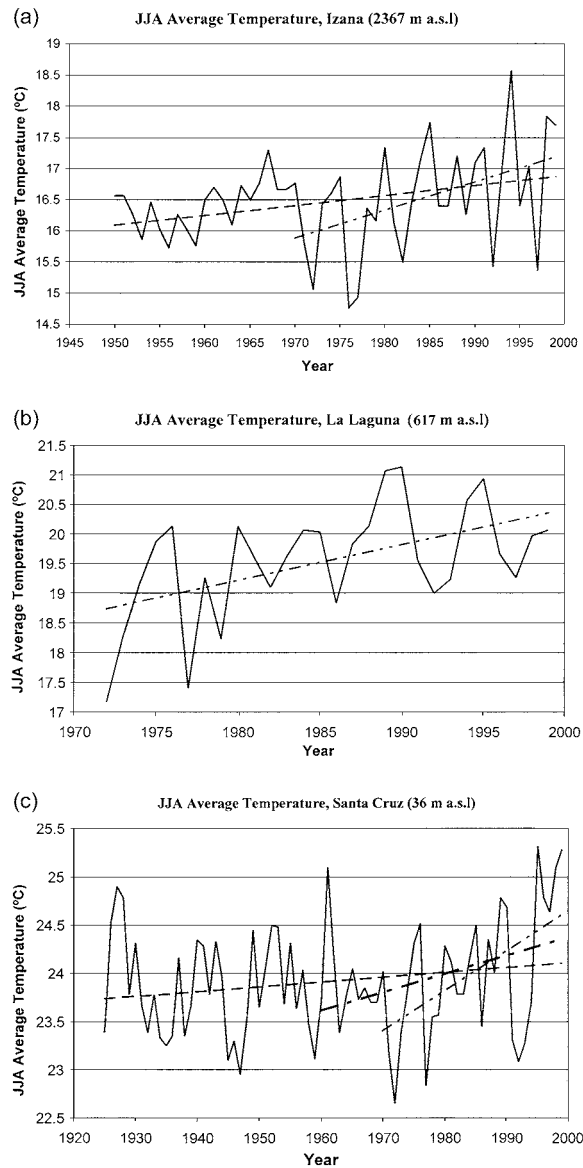


Figure 1. JJA seasonal temperature averages shown for (a) Izana, (b) La Laguna (Aeropuerto Norte) and (c) Santa Cruz. A significant warming trend of 0.16°C per decade can be detected for Izana (2367 m a.s.l.) from 1950–1999 ($p = 0.029$; dashed trend-line), from 1970 onwards a decadal warming trend of about 0.45°C is observed ($p = 0.005$, dash-dotted trend-line). At mid-elevations, within the recordings for La Laguna (617 m), a warming trend of 0.60°C can be detected from 1972–1999 (dashed trend-line). No significant rise in temperature can be found near sea-level at Santa Cruz (36 m) for the entire continuous recording period from 1925 to 1999 (dashed trend-line), but significant warming occurred during the last 30 and 40 years with $p = 0.030$ and 0.003 , respectively (dash-dotted and dotted trend-lines).

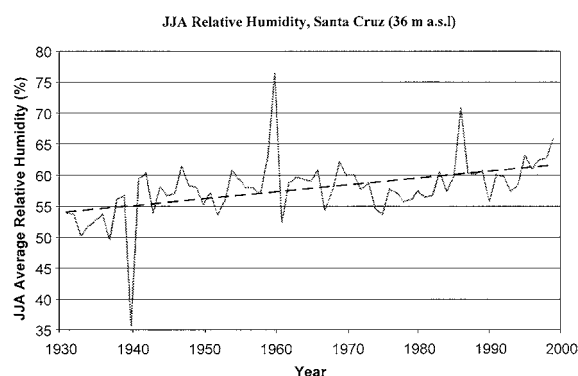


Figure 2. The JJA seasonal average of relative humidity at Santa Cruz shows an increase in relative humidity from 1931 to 1999 ($p < 0.001$).

pronounced on the windward slope of the island, where orographic cloud formation predominantly occurs during the dry season (Figure 3b). In contrast, at Izaña, above the tradewind inversion, where the incidence of cloud during the dry season is negligible, a significant increase in the diurnal temperature range is found for the same time period from 1974 to 1997 ($p = 0.005$), and no trend for the entire record from 1950 to 1999 can be detected (Figure 3c). In this context, it is interesting to point out that the diurnal temperature range of Santa Cruz (36 m a.s.l., leeward side) decreases from 1974 to 1997 ($p < 0.01$) as well as for the entire recording period from 1925 to 1999 ($p < 0.001$) (Figure 3a). The decrease in the diurnal temperature range of Santa Cruz from 1974 to 1997 was less pronounced than for the low altitude location on the windward side of the island (Figure 3b). The limited data are thus indicative of a long-term decrease in the diurnal temperature range during the dry season due to increased moisture and cloud cover below the tradewind inversion while at higher altitudes the range in diurnal temperatures may have increased.

Each of the GCM simulations returns a warming trend for the region of the Canary Islands for the JJA dry season, reflecting the findings in the observational data records. The warming trend is highly significant at the 0.001 level at all available pressure levels for the reference period from 1960 to 2099 and for the entire data set of each of the CGCM1 and ECHAM4 runs. The differences in temperature between the 2061–2090 and the 1961–1990 averages generally increase with altitude (Figure 4a). While the results obtained from ECHAM4, CGCM1 and CSIRO agree in the sign of the signal, they differ in its magnitude. CGCM1 shows the strongest change in temperature. The change is smallest in the CSIRO results, which also shows the lowest increase in temperature above 800 hPa.

Specific humidity represents the ratio of the mass of water vapor to the mass of moist air; i.e., it is an absolute measure of the amount of water available at a given level of the atmosphere. The GCM simulations each project an increase ($p < 0.001$) in specific humidity between the current climatic baseline and the

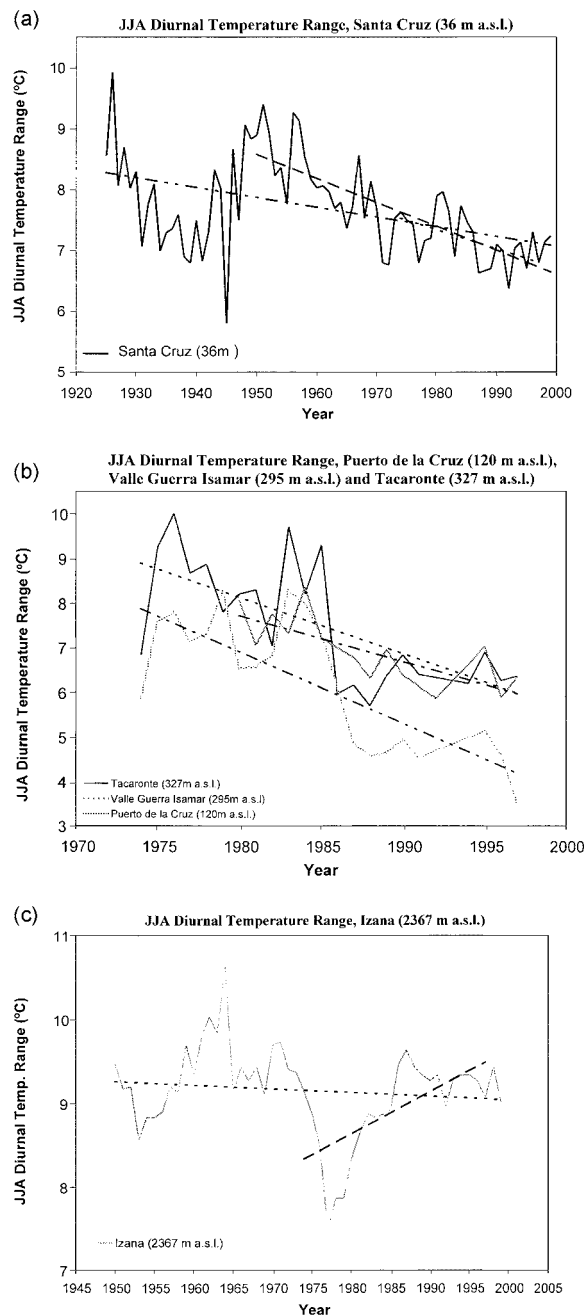


Figure 3. JJA diurnal temperature ranges over time. The data records for (a) Santa Cruz near sea-level from 1925–1999 (dash-dotted trend-line), and on the windward slope of the island for (b) Puerto de la Cruz from 1980–1997 (dash-dotted trend-line), Valle Guerra Isamar and Tacaronte from 1974–1997 (double dot-dash and dotted trend-lines) all show a significant decrease in the diurnal temperature range with time below the tradewind inversion ($p \leq 0.05$). Above the tradewind inversion a significant increase in the diurnal temperature range can be observed from 1974–1997 (dashed trend-line), while no significant trend is detected for the entire recording period from 1950–1999 (dotted trend-line).

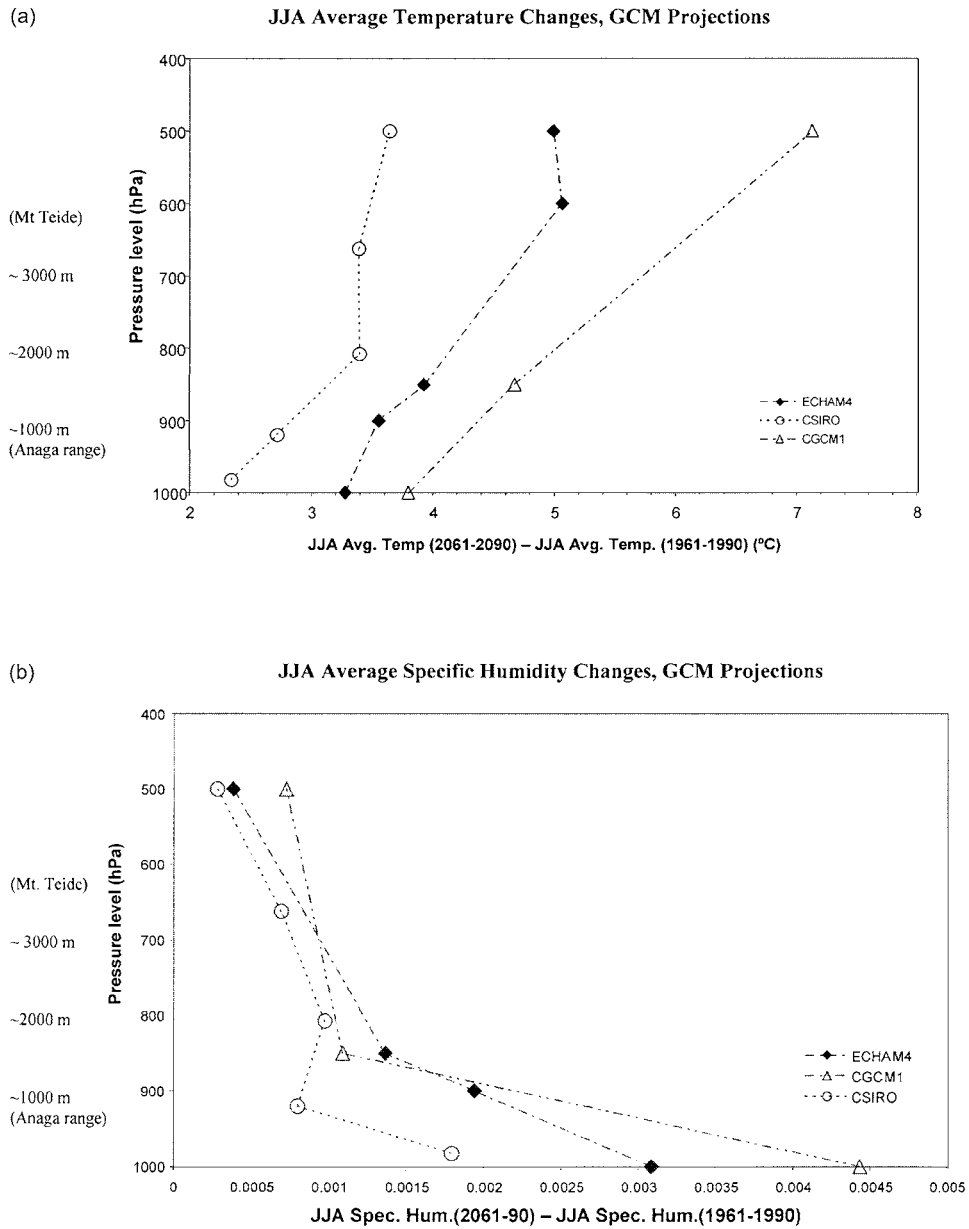


Figure 4. Differences in (a) the JJA average temperature and (b) specific humidity of the 30 year mean from 2061–2090 with respect to the 1961–1990 baseline obtained from ECHAM4 (diamonds), CSIRO (circles) and CGCM1 (triangles) at various pressure levels.

2061 to 2090 average at all vertical levels analysed (Figure 4b). CGCM1 exhibits the highest absolute change in specific humidity at the surface level and at 500 hPa. At the surface, the increase in specific humidity is approximately 50% higher than in ECHAM4 and is more than double the value for CSIRO (if its simulated value for specific humidity at 982.19 hPa is linearly extrapolated to 1000 hPa). The change in specific humidity at 850 hPa is more pronounced in ECHAM4 than in CGCM1.

Since relative humidity is a non-linear function of specific humidity and temperature (e.g., Jacobson, 1999), changes will be influenced by the relative magnitude of change of these two variables under the IS92a scenario. CGCM1 and ECHAM4 differ in their absolute relative humidity values but both indicate an increase at surface level between 1961–1990 and 2061–2090 ($p < 0.001$; Figure 5). No significant change in relative humidity was detected for the record length available for analysis in the CSIRO simulation. It was shown above that the CSIRO model produced the smallest relative increases in temperature and specific humidity, i.e., the changes in temperature appear to be counterbalanced by the changes in the moisture content of the atmosphere.

As orographic cloud formation occurs on the windward slopes, an increase in relative humidity implies that a greater amount of moisture is available for condensation. As cloud formation generally occurs when local values of relative humidity exceed 100%, the results of the ECHAM4 and CGCM1 runs suggest that in a warmer world the cloud base would shift downward. An indicative shift in the JJA seasonal cloud base height is obtained by subtracting the 2061–2090 mean from the 1961–1990 mean of the lifting condensation level after they have both been calculated from the dew point depression (Figure 6). As our results are based on grid-box averages and do not take microclimatic factors into account, it may be more realistic to focus on relative shifts in altitude rather than absolute values. However, since the calculations are based on estimates of the atmospheric moisture content in the region, these average values may still be indicative of climatic changes in respect of those the parts of the Canary Islands where cloud formation plays an important ecological role during the dry season. The most pronounced downward shift in the lifting condensation level is observed in the CGCM1 simulation, with an average depression of about 58 m in altitude ($p = 0.001$). ECHAM4 also indicates a downward shift of 20 m ($p \leq 0.05$). CSIRO, in contrast, shows a slight upward shift, which, however, remains within the variability simulated in the model and is not statistically significant.

With increasing altitude, the positive trend in relative humidity appears to weaken (Figure 7). In particular, CGCM1 shows a reversal of the trend at 850 hPa and 500 hPa ($p \leq 0.001$, Figures 7a,b). Thus, in contrast to the simulated trends in relative humidity at the surface, the model suggests a drying trend at higher elevations in the atmosphere. These findings are partly supported by ECHAM4. While a positive trend in relative humidity is observed at the surface and at 900 hPa ($p < 0.001$), no trend is found at 850 hPa. No significant trend can be found at 600 and 500 hPa for the reference period from 1960–2099. However, when the entire

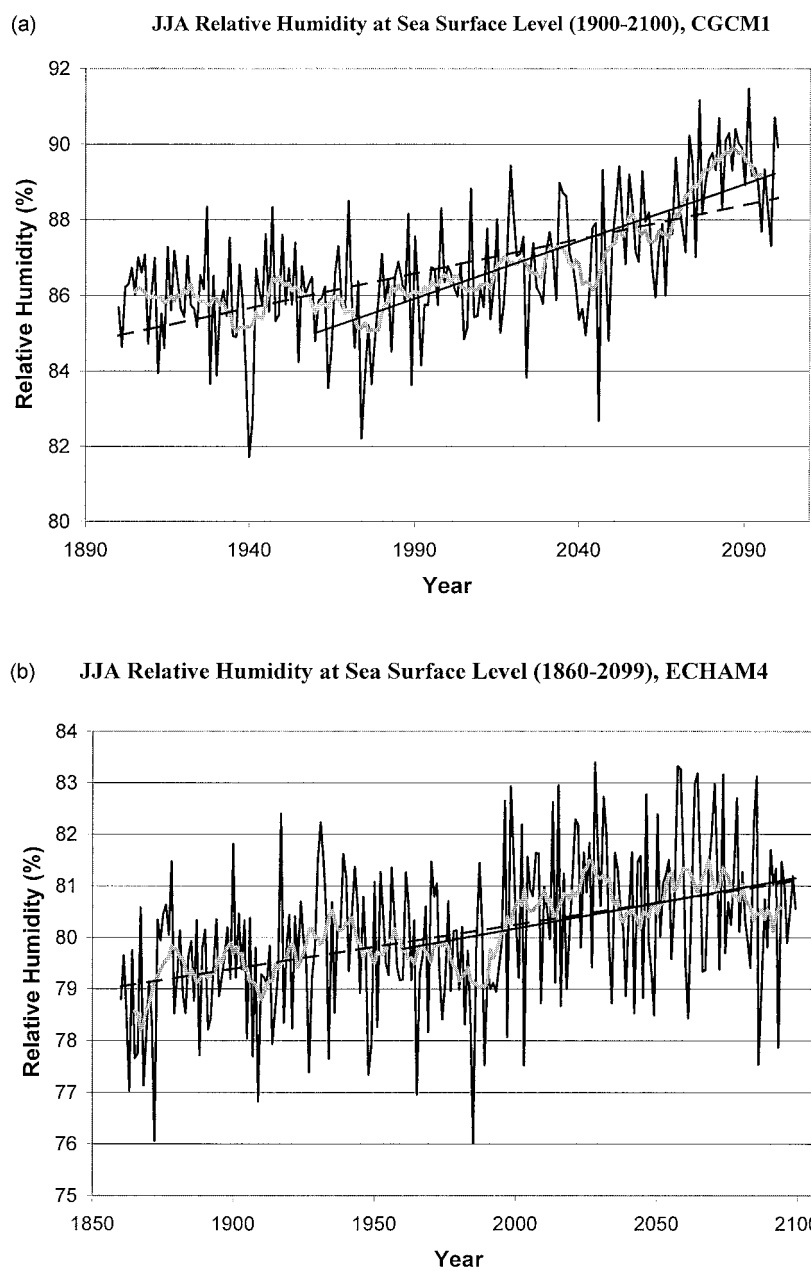


Figure 5. JJA average relative humidity over time at surface level showing the values obtained from (a) the CGCM1 run from 1900–2100 and (b) ECHAM4 from 1860–2099 under historic and IS92a greenhouse gas radiative forcing. Both models show a significant upward shift in average relative humidity from the 1961–1990 to the 2061–2090 mean ($p \leq 0.01$).

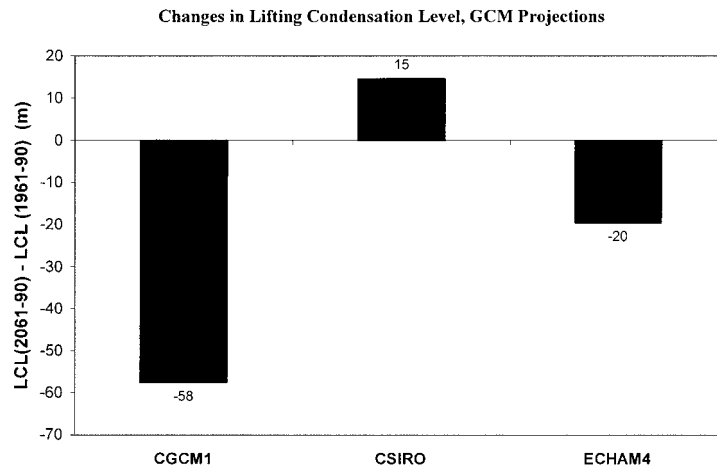


Figure 6. Differences in the lifting condensation level between the 30-year means of 2061–2090 and 1961–1990 during the dry season as suggested by the model simulations of CGCM1, CSIRO and ECHAM4 under the IS92a scenario.

model run of 240 years is considered, a significant drying trend is found at 600 hPa ($p < 0.025$; Figure 7c). The results of the CSIRO run display no significant change in relative humidity at 982.9, 919.8, 807.3 or 500.0 hPa. At 661.9 hPa a significant increase in relative humidity is observed ($p \leq 0.05$).

5. Discussion and Conclusions

Two of the three GCM simulations suggest that, under the IS92a scenario, a downward shift of the average cloud base level is likely by 2100 for the region of the Canary Islands during the dry season as compared with the present. These findings are supported by observed data from Tenerife which show significant increases in relative humidity and reduced diurnal temperature ranges over the last few decades below the trade wind inversion: these data imply an increased occurrence of low level clouds.

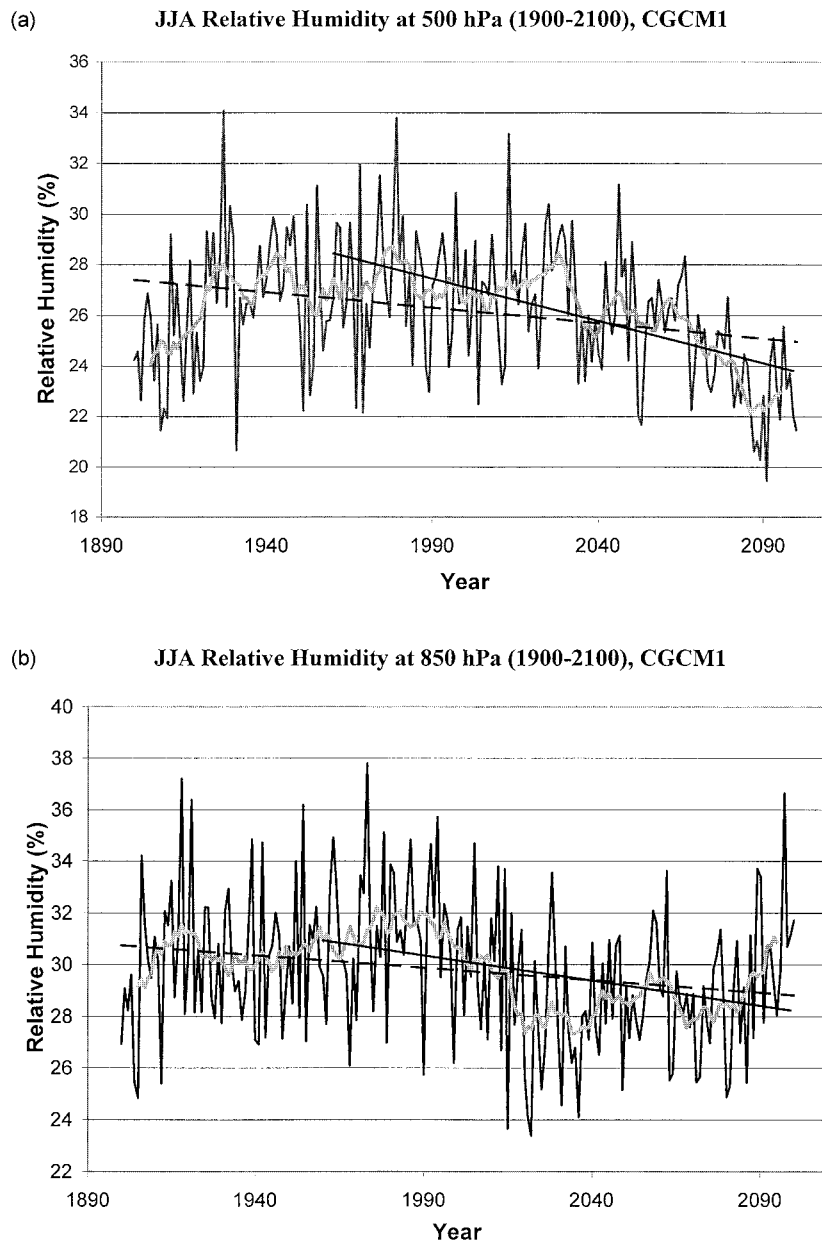
This suggests that the climatically suitable range for cloud forests is likely to be extended downwards in a warmer world, since the limiting effects of thermal and hydric stress would be reduced at these elevations during the dry season. Such a downward shift would increase the potential area climatically suitable for cloud forest. However, a downward shift of cloud forest patches may not necessarily follow. In addition to magnitude and rate of changes in climatic conditions, soil characteristics are important and, crucially, competing land-use practices have to be taken into account (Fernández-Palacios and Martín Esquivel, 2001).

The upper cloud forest border on Tenerife coincides roughly with the average altitude of the tradewind inversion. There is partial support in the model simulations – showing significant decreases in relative humidity from the present to

the end of the 21st century – that a warming of the atmosphere could lead to a drying trend at and above the tradewind inversion in the region of the Canary Islands. Given the location of the islands at the poleward limb of the Hadley Circulation, these findings may suggest a strengthened subsidence of dry, warm air and a lowering of the tradewind inversion, which determines the limit of the cloud tops. The significant increase in the diurnal temperature range observed within the last 30 years above the tradewind inversion at Izaña supports this drying trend. In addition, the simulations project that the warming trend in temperature over the 21st century increases with altitude. Consequently, the upper cloud forest border would be more frequently exposed to higher temperatures and intense radiation as it would be swathed by clouds less often during the dry season. The reduced incidence of clouds at these elevations would not only threaten the upper limit of the cloud forest belt, but could have considerable consequences as these regions represent the few areas of the island with a positive water balance throughout the year (Höllermann, 1981). Hence, the future location of clouds on the Canary Islands and therefore the potential climate space for the laurel forests may not only be influenced by changes to the regional temperature profile and moisture supply, but also by larger-scale changes in the atmospheric circulation.

As cloud forests are characterized by a large number of endemic species, fulfill important ecosystem services such as watershed protection, and are closely linked to climatic parameters, monitoring changes in climatic conditions and species composition in cloud forest locations may reveal important insights into fingerprints of climate change. Pronounced changes in climatic conditions are likely to affect the species composition of laurel forest communities. A study of dominant species along an altitudinal transect in the Anaga mountain range suggests that *Laurus azorica*, *Octoea foetens* and *Prunus lusitanica* are ‘climax’ canopy trees in fertile and humid valley habitat (Ohsawa et al., 1999). *Myrica faya* and *Erica arborea* characterise cloud forest patches characterized by more intense light due to natural and human induced disturbance (Fernández-Palacios and Arévalo, 1998). Shrubby heath communities, comprised largely of *Erica platycodon* and *Teline canariensis*, appear to dominate in nutrient and moisture limited areas, windswept mountain ridges, as well as regions where the initial laurel forest community has been disturbed (Höllermann, 1981; Ohsawa et al., 1999). Given these characteristics a drying trend at the upper cloud forest border would favor the heath community. In central parts of Tenerife, on slopes extending to the Las Cañadas plateau and Mt Teide, the endemic pine, *Pinus canariensis*, may also be favored at the upper cloud forest slopes, since it occupies the zone above the laurel forest, and is thus less strongly associated with the distribution of clouds (Höllermann, 1978).

The hypothesis of an increased subsidence and an associated downward shift of the tradewind inversion is based upon limited observational data and the results derived from the CGCM1 simulation, partly supported by the ECHAM4 simulation. Establishing a long-term monitoring network along altitudinal transects measuring relative humidity, horizontal precipitation, radiation intensity and wind direction

*Figure 7a, b.*

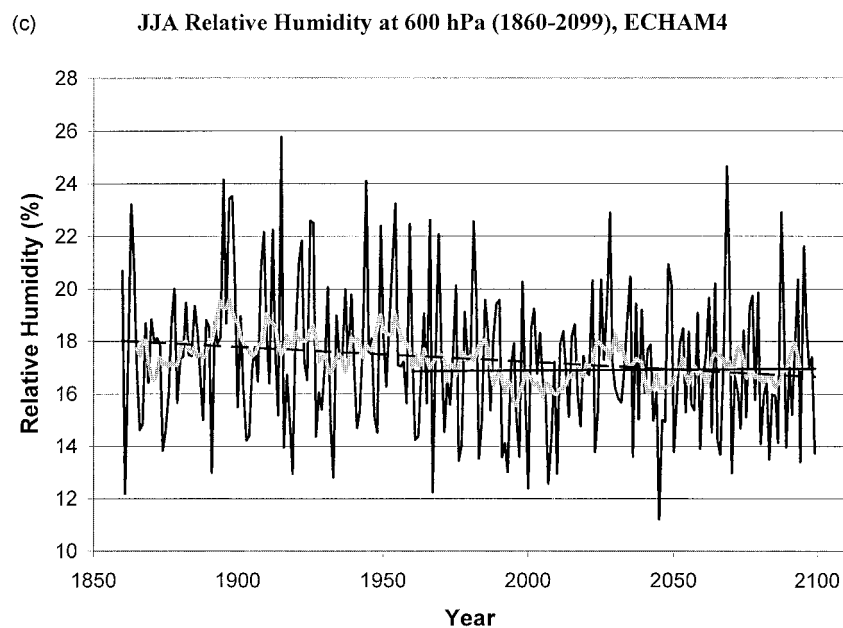


Figure 7c.

Figure 7. Simulated JJA seasonal averages of relative humidity at elevations near and above the tradewind inversion. Significant decreases ($p \leq 0.001$) in relative humidity at (a) 500 hPa and (b) 850 hPa are shown for CGCM1 for the reference time period common to all three model runs from 1960–2099 (full trend-line). A drying trend ($p < 0.025$) can be detected at 600 hPa in the ECHAM4 simulation when the entire model run from 1860–2099 is considered (dashed trend-line).

would help to test this hypothesis in the field. If the hypothesis were to hold, a decrease in relative humidity with time for upper cloud forest locations in the region of 1000–1500 m a.s.l. during the dry season could be expected. Furthermore, a reduction in horizontal precipitation would be experienced, particularly at cloud forest sites situated on the windswept mountain crests of the Anaga range, where the deposition of water droplets through direct contact of clouds with vegetation is considerable under present conditions (Kämmer, 1974). Study of the thermic inversion would aid the testing of this hypothesis. Examining changes in the dominant wind direction might further help to reveal changes in the atmospheric circulation that affect the moisture supply to the island.

The conclusions drawn from the analysis of the transient GCM simulations for the cloud formation in the region of the Canary Islands and the resulting implications for the cloud forests are opposite of the findings of Still et al. (1999) for tropical montane cloud forest locations, where an upward shift of the cloud base is suggested. The different findings may be explained by the different methodological approach taken in the study. Still et al. (1999) arrive at the relative shift in the cloud base by examining where a target relative humidity at the altitude of the cloud

forest site under current climatic conditions (control) is reproduced in a $2 \times \text{CO}_2$ world. In our analysis we take a different approach. We also recognize that the topography of the Canary Islands is not resolved in the GCM grid boxes. However, the values of temperature, absolute and relative humidity give us an indication of changes in the moisture supply to the islands and associated implications for cloud formation. By comparing surface relative humidity and LCL levels under current (1960–1990) and future (2060–2090) climatic conditions we gain an insight into the direction of change. The findings of the model simulations were compared with data on temperature, diurnal temperature range and relative humidity. As the direction of change in two of the three models is in agreement with the observed trend, we conclude that a downward shift or no change of the cloud base is more likely than an upward shift. It is interesting to note that the divergent findings of the two studies based on climate simulations are both supported by the analysis of observational data. While the contrasting projections may be rooted in the different methodological approach taken, it may also be possible that the observed trends are pointing to different regional effects of climate change on the distribution of the cloud base height in tropical and subtropical cloud forest locations and may be linked to their relative location in the Hadley Circulation.

In general, some ambiguity remains and the results have to be treated with caution, because microclimatic factors are not taken into account in the model simulations. Our results provide largely qualitatively insights into the likely direction of change of climatic parameters relevant to the ecology of cloud forests. It would be beneficial to develop a limited area model for a better representation of mesoscale climatic features. This would allow us to explore in more detail how the impact of climate change in subtropical and tropical cloud forest locations may differ. In conjunction with a GIS based platform, insights into the potential implications of climate change for the spatial distribution of laurel forests and consequences for conservation strategies could be obtained.

Acknowledgements

The authors would like to thank José María Fernández-Palacios and José Ramón Arévalo for providing valuable insights into the ecology of Tenerife, and the Centro Meteorológico Territorial de Canarias Occidentales of the Canary Islands for supplying meteorological data for Tenerife and the journal's referees for constructive criticisms of an earlier draft of this paper. The support of Barrie Hunt of CSIRO in obtaining and processing the data and Hans Luthardt of the Deutsches Klimarechenzentrum for providing access to the ECHAM4 database is greatly acknowledged. We are also grateful for access to the data of CGCM1 runs provided by the Canadian Centre of Climate Modelling and Analysis. Frank Sperling was supported by travel grants from Oxford University and Linacre College, and thanks Mike Bithell for advice on computing and insightful comments.

References

- Ballacado, J. J.: 1976, 'Notas Sobre la Distribucion y Evolucion de la Avifauna Canaria', in Kunkel G. (ed.), *Biogeography and Ecology of the Canary Islands*, Junk Publisher, The Hague.
- Bramwell, D.: 1972, 'Endemism in the Flora of the Canary Islands', in Valentine, D. H. (ed.), *Taxonomy, Phytogeography and Evolution*, Academic Press, London.
- Bramwell, D.: 1976, 'The Endemic Flora of the Canary Islands', in Kunkel G. (ed.), *Biogeography and Ecology of the Canary Islands*, Junk Publisher, The Hague.
- Bramwell, D.: 1990, 'Conserving Biodiversity in the Canary Islands', *Ann. Missouri Botanical Garden* **77** (1), 29–37.
- Bryan, K.: 1969, 'Climate and the Ocean Circulation. Part III: The Ocean Model', *Mon. Wea. Rev.* **97**, 806–827.
- Carlquist, S.: 1974, *Island Biology*, Columbia University Press, New York.
- Cox, M. D.: 1984, 'A Primitive Equation, Three-Dimensional Model of the Ocean', *GFDL Ocean Group Tech. Report. No. 1*, GFDL, Princeton University, Princeton, NJ, p. 141.
- de Nicolás, J. P., Nieto, E., Carbrera, P. G., Fernández-Palacios, J. M., and Ferrer, F. J.: 1989, 'Variacion de la Correlación netre la Diversidad y el Biovolumen de la Vegetacion sobre un Gradiente Altitudinal', *Studia Oecol.* **1**, 109–130.
- Eguchi, T., Wildpret, W., de Arco, M., and Reyes-Betancort, A.: 1999, 'Synoptic Analysis of Thermal and Moisture Conditions in Anaga, Tenerife, the Canary Islands' in Ohsawa, M., Wildpret, W., and de Arco M. (eds.), *Anaga Cloud Forest*, Laboratory of Ecology, Chiba University, Japan, pp. 23–38.
- Fernández-Palacios, J. M. and de Nicolás, J. P.: 1995, 'Altitudinal Pattern of Vegetation Variation on Tenerife', *J. Veg. Sci.* **6**, 183–190.
- Fernández-Palacios, J. M. and Arévalo, J. R.: 1998, 'Regeneration Strategies of Tree Species in the Laurel Forest of Tenerife (the Canary Islands)', *Plant Ecol.* **137**, 21–29.
- Fernández-Palacios, J. M. and Martín Esquivel, J. L.: 2001, *Naturaleza de las Island Canarias: Ecología y Conservación*, Publicaciones Turquesa S. L., Santa Cruz de Tenerife.
- Fernandopulle, D.: 1976, 'Climatic Characteristics of the Canary Islands', in Kunkel, G. (ed.), *Biogeography and Ecology of the Canary Islands*, Junk Publisher, The Hague, pp. 185–207.
- Flato, G. M., Boer, G. J., Lee, W. G., McFarlane, N. A., Ramsden, D., Reader, M. C., and Weaver, A. J.: 2000, 'The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate', *Clim. Dyn.* **16**, 451–467.
- Gordon, H. B. and O'Farrell, S. P.: 1997, 'Transient Climate Change in the CSIRO Coupled Model with Dynamic Sea Ice', *Mon. Wea. Rev.* **125**, 875–907.
- Hastenrath, S.: 1991, *Climate Dynamics of the Tropics*, Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Höllermann, P.: 1978, 'Geoecological Aspects of the Upper Timberline in Tenerife, Canary Islands', *Arct. Alp. Res.* **10**, 365–382.
- Höllermann, P.: 1981, 'Microenvironmental Studies in the Laurel Forests of the Canary Islands', *Mount. Res. Dev.* **1**, 193–207.
- Huetz de Lemps, A.: 1969, *Le climate des Iles Canaries*, Faculté des Lettres et des Sciences Humaines de Paris-Sorbonne, Paris.
- Intergovernmental Panel on Climate Change (IPCC): 1990, in Houghton, J. T., Jenkins, G. J., and Ephraums, J. J. (eds.), *Climate Change. The IPCC Scientific Assessment*, Cambridge University Press, Cambridge.
- Intergovernmental Panel on Climate Change (IPCC): 1992, in Houghton, J. T., Callander, B. A., and Varney, S. K. (eds.), *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.

- Intergovernmental Panel on Climate Change (IPCC): 1996a, in Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., *Climate Change 1995. The Science of Climate Change*, Cambridge University Press, Cambridge.
- Intergovernmental Panel on Climate Change (IPCC): 2001, in Houghton et al. (eds.), *Climate Change 2001: The Scientific Basis*, Technical Summary of the Working Group I Report, Cambridge University Press, Cambridge.
- Jacobson, M. Z.: 1999, *Fundamentals of Atmospheric Modelling*, Cambridge University Press, Cambridge, England.
- Kämmer F.: 1974, 'Klima und Vegetation auf Tenerife besonders im Hinblick auf den Nebelniederschlag', *Scripta Geobot.* **7**, p. 78.
- Lawton, R. O., Nair, U. S., Pielke, R. A., and Welch, R. M.: 2001, 'Climatic Impact of Lowland Deforestation on nearby Montane Cloud Forests', *Science* **294**, 584–587.
- Leggett, J., Pepper, W. J., and Swart, R. J.: 1992, 'Emission Scenarios for the IPCC: An Update', in Houghton, J. T., Callander, B. A., and Varney, S. K. (eds.), *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.
- López-Gómez, J. and López-Gómez, A.: 1979, 'El Clima de Canarias Según la Clasificación de Köppen', *Estudios Geográficos* **40**, C.S.I.C., Madrid.
- Machado, A.: 1976, 'Introduction to a Faunal Study of the Canary Islands' Laurisilva, with Special Reference to the Ground Beetles', in Kunkel, G. (ed.), *Biogeography and Ecology of the Canary Islands*, Junk Publisher, The Hague.
- McFarlane, N. A., Boer, G. J., Blanchet, J-P., and Lazare, M.: 1992, 'The Canadian Climate Centre Second-Generation General Circulation Model and its Equilibrium Climate', *J. Climate* **5**(10), 1013–1044.
- McGuffie, K. and Henderson-Sellers, A.: 1997, 'A Climate Modelling Primer', 2nd edition, Wiley and Sons, Chichester.
- Melville, R.: 1979, 'Endangered Island Floras', in Bramwell, D. (ed.), *Plants and Islands*, Academic Press, London, pp. 361–377.
- Morales, D., Jiménez, M. S., González-Rodríguez, A. M., and Cermák, J.: 1996, 'Laurel Forests in Tenerife, Canary Island', *Trees* **11**, 34–40.
- Oberhuber, J. M.: 1993, 'Simulation of the Atlantic Circulation with a Coupled Sea Ice – Mixed Layer – Isopycnal General Circulation Model. Part I: Model Description', *J. Phys. Oceanogr.* **22**, 808–829.
- Ohsawa, M., Shumiya, T., Nitta, I., Wildpret, W., Del Arco, M., and Reyes-Betancort, A.: 1999, 'Structure and Differentiation of Cloud Forests along Topographical Gradients in Anaga Mountains, Tenerife, the Canary Islands', in Ohsawa, M., Wildpret, W., and Del Arco, M. (eds.), *Anaga Cloud Forest. A Comparative Study on the Evergreen Broad-leaved Forest and Trees in the Canary Islands and Japan*, Laboratory of Ecology, Chiba University, Chiba, Japan, pp. 67–87.
- Parry, M. and Carter, T.: 1998, *Climate Impact and Adaptation Assessment*, Earthscan Publications, London, p. 166.
- Pounds, J. A., Fodgen, M. P. L., and Campbell, J. H.: 1999, 'Biological Response to Climatic Change on a Tropical Mountain', *Nature* **398**, 411–415.
- Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Dümenil, L., Esch, M., Giorgetta, M., Schlese, U., and Schulzwida, U.: 1996, *The Atmospheric General Circulation Model ECHAM-4: Model Description and Simulation of Present Day Climate*, Report No. 218, Max Planck-Institute für Meteorologie, Hamburg, Germany, p. 90.
- Still, C. J., Foster, P. N., and Schneider, S. H.: 1999, 'Simulating the Effects of Climate Change on Tropical Montane Cloud Forests', *Nature* **398**, 608–610.

- Thompson, S. L. and Pollard, D.: 1997, 'Greenland and Antarctic Mass Balances for Present and Doubled CO₂ from the Genesis Version-2 Global Climate Model', *J. Climate* **10**, 871–900.
- Voggenreiter, V.: 1974, 'Geobotanische Untersuchungen and der natürlichen Vegetation der Kanareninsel Tenerife als Grundlage für den Naturschutz', *Dissertat. Botanicae* **26**, Cramer Verlag, Lehre, p. 718.

(Received 1 November 2001; in revised form 9 September 2003)