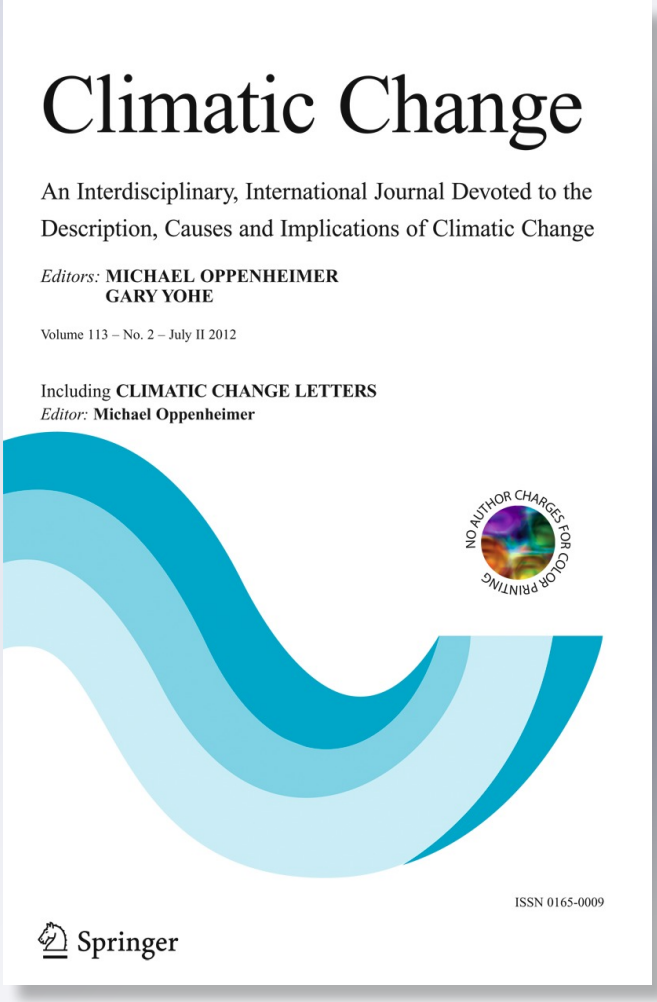
Assessment of global warming on the island of Tenerife, Canary Islands (Spain). Trends in minimum, maximum and mean temperatures since 1944

José L. Martín, José Bethencourt & Emilio Cuevas-Agulló

Climatic Change
An Interdisciplinary, International Journal Devoted to the Description, Causes and Implications of Climatic Change

ISSN 0165-0009
Volume 114
Number 2

Climatic Change (2012) 114:343-355
DOI 10.1007/s10584-012-0407-7



Springer

Climatic Change (2012) 114:343–355
DOI 10.1007/s10584-012-0407-7

Assessment of global warming on the island of Tenerife, Canary Islands (Spain). Trends in minimum, maximum and mean temperatures since 1944

José L. Martín · José Bethencourt · Emilio Cuevas-Agulló

Received: 26 July 2011 / Accepted: 16 January 2012 / Published online: 16 February 2012

Abstract Temperature variation is studied at different altitudes and orientation on the island of Tenerife, according to the trends in the mean, maximum and minimum at 21 meteorological stations. Reference series are obtained by sectors, along with a representative overall series for Tenerife, in which temperature shows a statistically significant growth trend of 0.09±0.04°C/decade since 1944. Night-time temperatures have risen most (0.17°C±0.04°C/decade), while by day they have been more stable. Consequently, the diurnal temperature range between day and night has narrowed. By regions, warming has been much more intense in the high mountains than the other sectors below the inversion layer between 600 and 1,400 m altitude, and progressively milder towards the coast. The temperature rise on the windward (north-northeast) slopes is greater than on the leeward side and could be related to the increase in cloudiness on the northern side. The general warming of the island is less than in continental areas at between 24 and 44ºN, being closer to the sea surface temperature in the same area. This is probably explained largely by the insular conditions. In fact warming is more evident in the high mountains (0.14±0.07°C/decade), where the tempering effect of the ocean and the impact of changes in the stratocumulus is weaker, being similar to the mean continental values in the northern hemisphere.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-012-0407-7) contains supplementary material, which is available to authorized users.

J. L. Martín (✉)
Canary Islands Agency for Climate Change and Sustainable Development,
Observatory of Sustainable Development, C/. Zarate y Penichet, 5,
38071 Santa Cruz de Tenerife, Spain
e-mail: jmaresq@gobiernodecanarias.org

J. Bethencourt
Canary Islands Agency for Climate Change and Sustainable Development,
38071 Santa Cruz de Tenerife, Spain

E. Cuevas-Agulló
Izaña Atmospheric Research Centre (AEMET), 38071 SC de Tenerife, Spain

1 Introduction

Global warming is an undeniable fact worldwide. The temperature of the planet has increased by 0.74±0.18°C, based on the linear trend between 1906 and 2005, in the second half of that period at a rate twice that in the first half (0.13±0.03°C/decade vs. 0.07±0.02°C/decade) (Trenberth et al. 2007). However, this rise is not happening simultaneously in all places, it is more pronounced in the northern than the southern hemisphere (Jones 1994; Jones et al. 1982, 2011) and at the poles than in tropical regions (Root et al. 2003). Since 1979, the rate of increase in surface temperatures on land has been more than double the ocean rate (0.27°C/decade against 0.13°C/decade) (Trenberth et al. 2007).

This excellent knowledge of the trend in global temperatures contrasts with relative unfamiliarity on a regional scale, particularly regarding oceanic islands, where there are only a few climate studies that include a wide variety of temperature data, for example Yue and Hashino (2003), Giambelluca et al. (2008) and Trueman and d'Ozouville (2010), among others. However, islands are of crucial importance owing to the vulnerability of their ecosystems to climate change (Loope and Giambelluca 1998; Sperling et al. 2004) and their providing a worldwide network of observatories for monitoring the effects of global warming (Petit and Prudent 2008). At the same time, the higher mountainous islands are natural laboratories where such trends can be studied at different altitudes, from the marine boundary layer to the free troposphere, and then extrapolated to large regions for which there is hardly any data, in our case with the rest of the subtropical North Atlantic ocean. Many climate models suggest an amplification of global warming in high mountains (Diaz and Bradley 1997; Pepin and Lundquist 2008), and highlight the important role of topography in long-term temperature trends (Pepin and Norris 2005). Climate is the result of a balance between the influence of air mass advections and surface radiation induced by local and regional factors, consequently the presence of clouds, slope orientation, different wind intensity and frequency, and closeness to the sea all play major roles in temperature.

The geomorphology of Tenerife, with a high altitudinal gradient and one slope facing south toward the equator and the other north, makes this island very conducive to investigating temperature changes in different scenarios. Several studies have found an increase in temperatures in the last century (Oñate and Pou 1996), but so far the warming has not been quantified exactly. Sperling et al. (2004) noted one of its possible consequences in cloud altitude during summer months and Sanroma et al. (2010) studied the effect of global dimming/brightening at two stations on Tenerife.

The aims of this paper are to: (1) quantify warming on Tenerife and in its different areas, taking into account differences in altitude and orientation; (2) determine how maximum and minimum temperatures behave over time and their influence on the diurnal temperature range (DTR), which is considered a well-known indicator of global warming (Braganza et al. 2004); (3) see how the extent of warming relates to global measurements of temperature in the northern hemisphere. The choice of Tenerife as model is due to its impressive relief, which allows studies in very different climatic and environmental settings.

1.1 Tenerife

Tenerife (27º60′–28º35′ N, 16° 05′–16′55′W) is the central island of the Canary archipelago and also the largest and highest. Despite being near the African continent, its climate is very different from that expected from its latitude, due to the powerful influence of the cool humid northeast trade winds, associated with the Azores anticyclone (Font 1956; Marzol 2001). It has a pyramidal shape with a maximum height of 3,717 m a.s.l. and an area of

2,034 km^2. The north is more humid than the south, especially at mid-altitudes, where the trade-wind influence leads frequently to a layer of stratocumulus known locally as 'sea of clouds', usually between 800 and 1,500 m a.s.l. The 'top' of these clouds is delimited by a thermal inversion layer, seasonally variable in altitude and strength (Font 1956; Dorta 1996).

2 Methodology

To facilitate trend analysis we applied a method to fill gaps, correct outliers and adjust inhomogeneities in the monthly series. Extreme outliers greater than the third quartile plus three times the interquartile range (=IQR) were removed for temperatures above the median, or less than the first quartile minus three times IQR in the case of temperatures below the median. Since IQR is sensitive to the length of series (Peterson et al. 1998), values higher than the mean plus three times the standard deviation (or lower than the mean minus three times the standard deviation) were also considered extreme outliers (Guttman and Quayle 1990). When the difference was between 1.5 and 3 times the IQR, the outlier was classified as suspect. We sought to remove the suspicion by interpolating from the data of other series with which it was acceptably correlated ($\geq$0.8).

Correlations were made between the 10 year time series, just before or after the outlying data in the same series, and other longer series without outliers, to serve as reference series. The outliers were interpolated by adjusting to the temperature for that year in the reference series, corrected according to the differential of the means between the correlated segments. When the new data did not remove the suspicion, the old data were left unchanged.

The months with no data and those where extreme outliers had been eliminated were filled in by the same interpolation system as for suspect outliers. When this was not possible or the interpolation was also an extreme outlier, the value was left blank.

A time series is said to be homogeneous when its variability is due solely to climatic causes, so that inhomogeneities are unnatural variations unique to each series. Inhomogeneity can be corrected using the series itself as a reference (absolute homogenization) or other supposedly homogeneous reference series that are long enough (relative homogenization). Both approaches are worthwhile and valid (Costa and Soares 2009), but absolute homogenization has the disadvantage of not discriminating false inhomogeneities resulting from natural jumps in climate or other causes. The metadata associated with each station may be essential in these cases (Costa and Soares 2009); however some alternative method is necessary to exclude false inhomogeneities when there is no such background information.

In general the monthly temperature series of Tenerife were poorly correlated, fragmented, and did not cover long periods (average, 26 years), so absolute homogenization was almost always the only option because of a lack of reference series. The series were homogenized by the Standard Normal Homogenization Test (SNHT) for a single break (Alexandersson 1986; Alexandersson and Moberg 1997) or that of Pettitt (1979), depending on the degree of normality. We used Anclim homogenization software as a tool for the analysis of time series (Stepanek 2007). Both tests are capable of locating the period (year) where a break (step-wise shift in the mean) is likely, comparing the series with itself or with another reference series. The null hypothesis in SNHT is that the data are independent, identically normally distributed random quantities, and the alternative is that a break is present. In every case the 95% confidence limit was used to classify the test parameter maximum as a break in homogeneity. SNHT only marks the first inhomogeneity it finds from

the earliest data onwards (Khaliq and Ouarda 2007), so the repetition of the test each time a change was introduced was particularly necessary.

To distinguish the true inhomogeneities, we sought to correlate short segments (10 years at least) containing breakpoints with equivalent sectors of all other series free of inhomogeneities. When no similar changes were seen in any other series, the inhomogeneity was considered true and the series was homogenized in the way explained below. Otherwise the inhomogeneity was considered false and no changes were made.

Absolute homogenization is an insufficiently investigated field (Venema et al. 2011). Despite some interesting work in this regard (Reeves et al. 2007), little has been said about the adjustments, so we chose a method that allows the homogenization with the least possible disruption of series. Adjustments were made by progressive simultaneous changes in the entire segment previous to the breakpoint and repetition of the SNHT to locate the statistical value within a 95% confidence limit. If inhomogeneities then reappeared in other parts of the series, they were adjusted in the same way. Normally the entire series was homogenized after a few steps such as these. To ensure that homogenization did not significantly alter the original series we used the Levene test for homogeneity (Levene 1960).

We use the method of climatic anomalies to analyse trends (Jones et al. 1982; Jones and Hulme 1996), so the first exercise was to set the baseline period. Given that a period of at least 30 years is recommended as baseline for calculating the anomalies (WMO 1996; Aguilar et al. 2003), we selected the years between 1970 and 1999 as more appropriate to ensure that all series are represented at the base period without a high proportion of gaps. Linear regressions were calculated for all series of anomalies, along with their degree of significance according to Spearman's rank test (Sneyers 1975). Whenever the compilation of the reference series included more than one station, an average series of anomalies was constructed, applying the approach developed by Osborn et al. (1997) to correct the bias in the variance due to the different number of stations considered each year. The statistical significance of the linear trends was assessed, accounting for temporal autocorrelation following the method described by Santer et al. (2000).

2.1 Meteorological stations

To achieve our aims we have attempted to cover the greatest possible variability of climates. After an analysis based on their altitude and orientation, length of series and complementarity between stations, the 36 stations in Fig. 1 were chosen. These stations are managed by the State Meteorological Agency of Spain (AEMET). Only 21 of the 36 working stations were used in the construction of zonal reference series, the others provided support in the correlations made during the processes of gap-filling, outlier correction or adjustment of inhomogeneities. In constructing the zonal reference series, stations were pooled with those of similar characteristics in terms of altitude and orientation. Four sectors were identified on the north side of the island (windward), four on the south side (leeward) and two in the high mountain area, each with the same altitude range of 400 m. Reference series were also compiled by grouping various sectors together, in which case the anomalies derived from the average across all the sectors were weighted according to their respective surface areas.

The series of stations in the sectors between 800 and 2,000 m a.s.l. proved too short and/or fragmented to allow trend analysis (the topology of each series is shown in the Electronic supplementary material), so they were only used as back-up support for the adjustments made in other areas. The longest series ranged from the mid-1970s in one case (sector K between 400 and 800 m in altitude a.s.l. and 30,393 ha in surface area in the south) and from the 1940s in the others (sectors: J, 0–400 m altitude and 42,555 ha

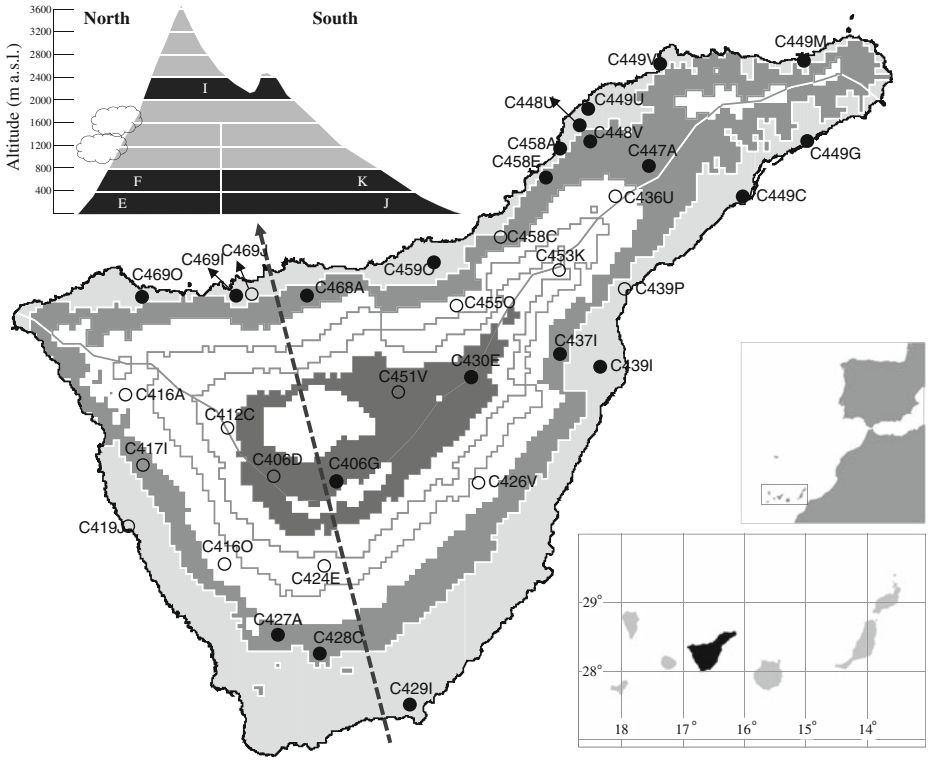


Fig. 1 Geographic location of the stations analysed. *Black spot*: stations used to construct zonal reference series. *Circle*: stations used as support in the correction of the other series

in area in the south; E, 0–400 m and 12,955 ha in the north; F, 400–800 m and 21,489 ha in the north; I, 2000–2400 m and 19,200 ha in the high mountain area). The data grouped by sector allowed the general reference series of the island and three zonal reference series to be built up: one for the north side, from the shore to 800 m (windward: series E+F), another for the south side at the same altitude (leeward: series J+K) and one for the high mountain above the stratocumulus layer between 2,000 and 2,400 m altitude (series I).

Figure 1 (vertical cross section) shows the geographical distribution of the series over the altitude belts. The individual reference series E, F, J, K and I were constructed from the averaging and adjustment of the variances of the stations included in them. The windward reference series was obtained by adjusting variances and averaging the two reference series E and F after weighting according to their respective surface areas. The same was done with J and K from the south-facing stations. The reference series for the island was again obtained by averaging the five reference series E, F, J, K and I, after the corresponding adjustment of variance and weighting.

3 Results

1,002 monthly temperature averages were used for gap-filling in 432 series of mean maximum temperature (36 stations × 12 months) and 432 mean minima, taking as reference

the best correlated monthly series. Most of these additions were made in February and March. Jump inhomogeneities were detected in 73 series of maxima and 134 of minima for the 21 stations used to obtain all the final zonal reference series. Most inhomogeneities in the maxima were concentrated in July, August and September, while those in the minima were distributed similarly throughout all months. The reference series for the north of the island (E+F) showed many more inhomogeneities in their minima than in the southern (J+K) and high mountain series (I), and series E had the most inhomogeneities recorded. In the series 449 G from San Andrés and C447A from Los Rodeos, relative homogenizations were performed from previously homogenized sections of C449C (Santa Cruz) and C468A (Guancha-Asomada), respectively.

The series of anomalies with respect to the 1970–1999 baseline period of mean temperatures for the island recorded a positive trend of 0.09±0.04°C/decade (α=0.01) between 1944 and 2010 (Table 1). The mean temperature anomaly for 2010 resulting from the linear regression of these anomalies between 1944 and 2010 was 0.32±0.16°C higher than the baseline period, but the mean anomaly over the last 10 years was 0.39±0.16°C above the baseline. The trend showed an even more pronounced increase in the 1970–2010 period: 0.17±0.09°C/decade. The comparison of the mean temperature of the ten most recent years (2001–2010) with that of the earliest 10 years (1944–1953) revealed an increase of 0.60±0.30°C.

Considering the island as a whole, the temperature has increased since 1944 mainly in summer, autumn and winter (Electronic supplementary material shows the seasonal trend). In parts of the island usually under the stratocumulus layer, warming is higher in autumn and

Table 1 Rate of warming in annual temperatures (*α=0.01; ** α=0.05; n.s. not significant)

		T_{ave}	T_{max}	T_{min}	DTR
Tenerife (whole island)					
Series E+F+J+K+I	°C/decade$_{(1944–2010)}$	0.09±0.04**	n.s.	0.17±0.04**	−0.16±0.04**
	$r_{(1944–2010)}^2$	0.21		0.50	0.65
	°C/decade$_{(1970–2010)}$	0.17±0.09**	n.s.	0.25±0.09**	−0.14±0.09**
	$r_{(1970–2010)}^2$	0.28		0,47	0,44
Windward slope below stratocumulus layer					
Series E+F	°C/decade$_{(1944–2010)}$	0.08±0.05**	n.s.	0.21±0.05**	−0.26±0.08**
	$r_{(1944–2010)}^2$	0.15		0.54	0.61
	°C/decade$_{(1970–2010)}$	0.16±0.10**	n.s.	0.30±0.10**	0.29±0.16**
	$r_{(1970–2010)}^2$	0.20		0.47	0.44
Leeward slope below stratocumulus layer					
Series J+K	°C/decade$_{(1944–2010)}$	0.06±0.04**	n.s.	0.12±0.04**	−0.11±0.07**
	$r_{(1944–2010)}^2$	0.13		0.31	0.30
	°C/decade$_{(1970–2010)}$	0.13±0.10**	n.s.	0.19±0.10**	n.s.
	$r_{(1970–2010)}^2$	0.14		0.29	
High mountains areas above stratocumulus layer					
Series I	°C/decade$_{(1944–2010)}$	0.14±0.07*	0.10±0.08*	0.18±0.06**	n.s.
	$r_{(1944–2010)}^2$	0.22	0.09	0.33	
	°C/decade$_{(1970–2010)}$	0.31±0.12**	0.29±0.14**	0.32±0.14**	n.s.
	$r_{(1970–2010)}^2$	0.38	0.32	0.36	

winter than in spring, while above the clouds the temperature rise has been mainly in winter, spring and summer. Since 1970, warming has intensified in spring, mainly in high mountain where the mean temperature in the last 10 years has become almost 1°C higher than the average in the baseline period.

The evolution of maxima and minima show asymmetric behaviour (Fig. 2). Whereas the former showed no statistically significant trend, the minima showed a mean positive growth trend of 0.17±0.04°C/decade (α=0.01) between 1944 and 2010, only interrupted by a short cooling in the 70s. As a result, the mean minimum for 2010, estimated from the linear regression since 1944, was 0.51±0.16°C above the mean minimum in the baseline period. The mean anomaly in the minima for the last 10 years also proved to be higher than the baseline period (0.53±0.16°C). This rate of growth in the minima has become more pronounced in the last four decades, during which it reached 0.25±0.09°C/decade. Climate variability, measured as the difference between the last 30 years and the previous 30, has also increased (Fig. 3).

The increase in mean minimum temperatures and the steadiness in maxima resulted in a notable narrowing of the DTR. The downward trend between 1944 and 2010 of −0.16± 0.04°C/decade (α=0.01). The DTR in 2010 resulting from the linear regression between the 1944 and 2010 was 0.38±0.11°C smaller than in the base period. It is noteworthy that the mean DTR over the last 10 years (2001–2010) turned out to be 0.85±0.33°C less than that of the earliest 10 years (1944–1953). By sectors, the change in DTR was more marked on the windward slopes than on leeward (Table 1).

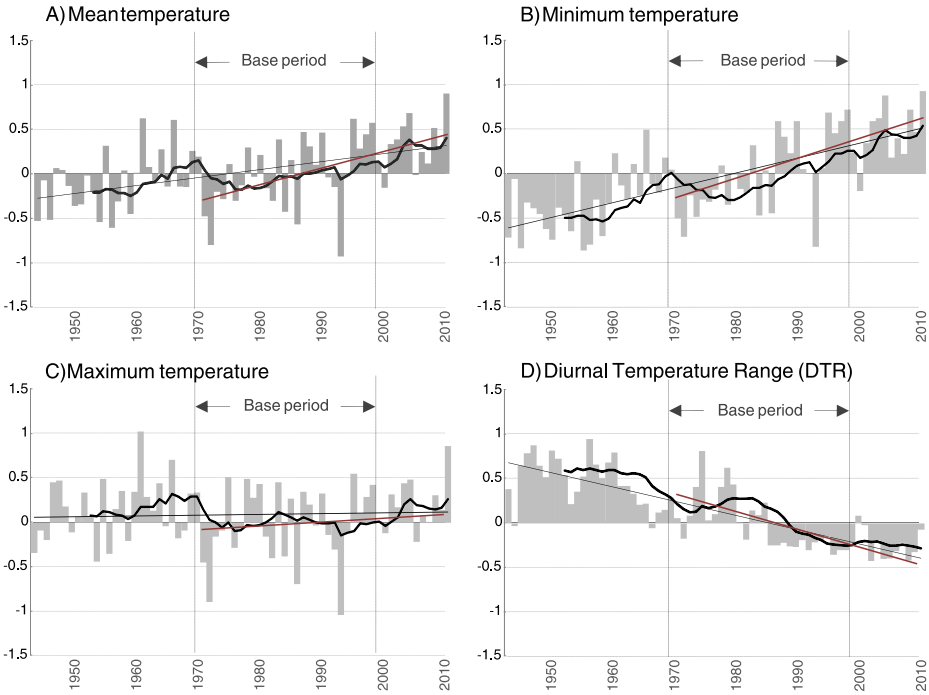


Fig. 2 Trend in the evolution of annual anomalies in temperatures on Tenerife. *The curve* represents the moving average factor 10, and the *lines* correspond to linear regressions for the periods 1944–2010 and 1970–2010, respectively

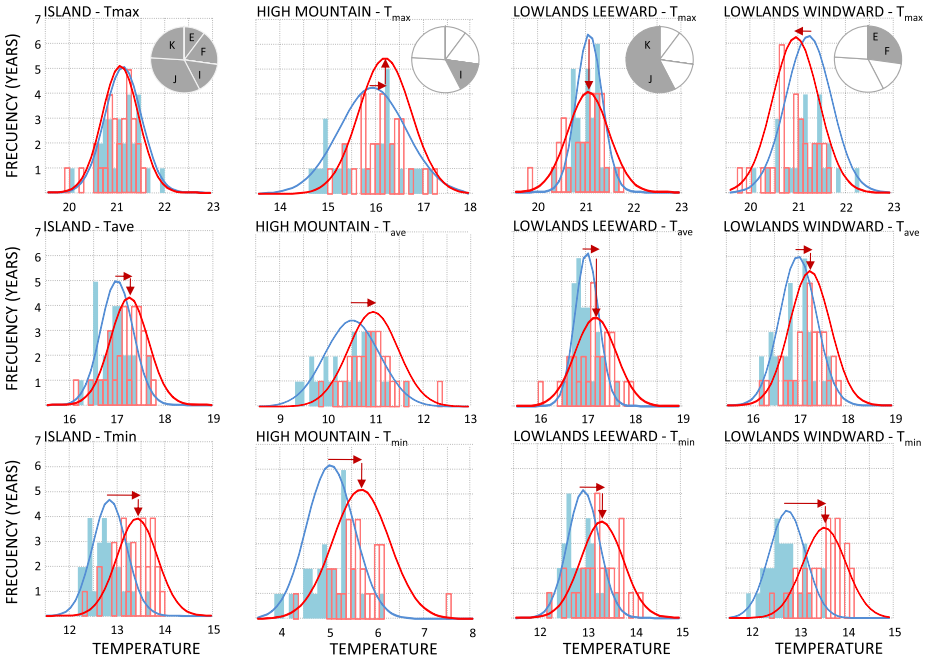


Fig. 3 Normal distribution of temperatures and frequency by 0.1°C degree intervals on windward and leeward slopes, comparing the new climate data (period 1981–2010: *red*) with the previous data (period 1944–1973: *blue*). The *circle* indicates the proportional surface area affected, and the *arrows* indicate the observed changes

The trends were different in the high mountain area (Table 1), where both maxima and minima increased significantly, compared to both windward and leeward slopes in the lowlands below 800 m a.s.l., in which maxima hardly show any different trend and the minima went through a statistically significant rise of 0.21±0.05°C/decade and 0.12±0.04°C/decade, respectively. The analysis of the latest series, considering only since 1970, shows a similar pattern but with more warming near the summit, slightly less in the north and in the south, less still. The main difference is the narrowing of the DTR below 800 m as a result of a considerable asymmetry in the increase of maxima and minima, with a wider difference on the windward side, while in the high mountain there was no significant change (Table 1).

Climate variability in general has tended generally to increase in all sectors (Fig. 3), but especially at stations under 800 m a.s.l., so that when comparing the data for the last 30 years (1981–2010) with the earliest 30 years in the windward and leeward sectors (1944–1953), we see a clear increase in the number of warm months and a drop in the number of cold months. The variability increased on leeward slopes (standard deviation changed from 0.25 to 0.43) while declining slightly on windward (from 0.42 to 0.38). Around the summit the situation is different: although the minima were more variable, the maxima were less so. The change in the maxima involved a decrease in the number of more moderate maximum values, but no increase in the number of more extreme warm values.

4 Analysis and discussion

The data indicate a temperature trend coinciding with the overall pattern observed in the northern hemisphere, especially in latitudes closer to the Equator (Wild 2009; Easterling et al. 1997). Figure 2 shows how, after a warming in the 1960s there came a cooling in the 70s, which once over, gave way to the current warming. The 1970s cooling coincided with global dimming with reduced sunlight described worldwide, probably due to excessive sulphur emissions (Liepert 2002; Smith et al. 2011); its records in the Canary Islands were reported by Sanroma et al. (2010). There was another slight short-term cooling in the early 90s, coinciding with darkening of the sky due to the ash emitted by the Pinatubo eruption.

One of the most striking patterns within the overall trend is the warming in the last decade, the most intense in the entire period. This coincides with a recent brightening reflecting the gradual increase in atmospheric transparency since the mid-eighties, as confirmed by measurements at the Roque de los Muchachos Astronomical Observatory on the nearby island of La Palma (Sanroma et al. 2010). This is consistent with the hypothesis that the actual warming effect is more pronounced than it appears, and only in recent times, when global dimming has become tempered, has its greater intensity been noticed (Andreae et al. 2005; Stott et al. 2008).

Another clear pattern is the differential evolution in the three zones of the island identified: high mountain and slopes. Warming near the summit is higher that in the lowlands, and although more intensely seen in the minimum readings, it is also reflected in the maxima. This fact was already noted by Oñate and Pou (1996) and has been observed in many other regions of the globe (Easterling et al. 1997; Brunet et al. 2007), including tropical islands like Hawaii (Giambelluca et al. 2008). The next most important zone in terms of magnitude of warming is the windward slope, where the growth is concentrated entirely in night-time temperatures. This asymmetry is also present on the leeward side but here the increase in the minima is less intense. The asymmetry in temperature evolution below the inversion level involves a considerable drop in the DTR, as also observed in other mountain regions (Weber et al. 1994; Pepin and Norris 2005).

Changes in DTR are often associated with variations in the radiative forcing due to changes in low clouds and soil moisture (Dai et al. 1999; Stone and Weaver 2002, 2003). On Tenerife, the greatest decline in DTR occurs on the northern slopes, where the trade-winds form the typical 'sea' of stratocumulus to windward. Sperling et al. (2004) hypothesized that the lower limit of this cloud layer could be losing altitude in summer, and the recently discovered poleward expansion of the Hadley cell associated with the constancy and frequency of the northeast trade-winds (Hu and Fu 2007; Seidel et al. 2008) could affect wind movement and consequently this layer. Climatological cloudiness databases categorize days as clear, cloudy or overcast. This 'flag' is obtained from the sum of the total cloud amount in Octas (Octa means one-eighth of the sky) observed by visual inspection at 07, 13 and 18 GMT. If that amount is less than 5, the day is considered as "clear", between 5 and 19 as "cloudy", and if the sum is greater than or equal to 20, the day is flagged as "overcast". In this study we have used cloudiness records from the aeronautical meteorological station C447A (632 m a.s.l.), at the older airport of the island, Los Rodeos, where very accurate cloudiness observations are performed. The number of cloudy days in this station shows a significant increase since 1961 with a positive trend of 9.24±3 cloudy days/decade (α=0.01, r^2=0.34) (Fig. 4). Station C447A is at one end of the Aguere Valley (600 m a.s.l.), the only natural corridor connecting the north and the south slopes of the island, where low clouds (stratocumulus) pass close to the ground. Therefore, this is a unique sentinel station for the study of long-term evolution of cloudiness, and specifically for stratocumulus driven by the trade-wind regime.

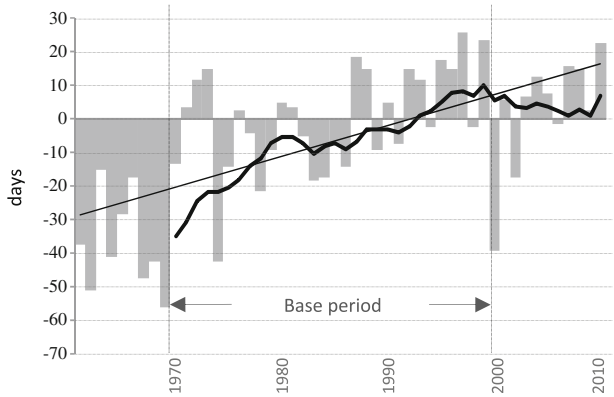


Fig. 4 Anomalies in the number of cloudy days in relation to the base period 1970–1999 at the station C447 (Rodeos). The *curve* represents the moving average factor 10, and the *lines* correspond to linear regressions for the period 1961–2010

The steadiness of the maxima in this area is consistent with this increased cloudiness, which would reduce sunlight and prevent their rising by day. At the same time, the increase in minima would be favoured by the stratocumulus cover impeding the escape of infrared radiation from the lower troposphere during the night. Although dimming due to clouds does not seem as significant in the Canaries as in other regions of the globe (Jensen et al. 2008), Klein and Hartmann (1993) estimated it at −30 W/m^2 for July in the Canary Islands, when low cloud cover is at its maximum extension and lowest altitude (Font 1956).

When the temperature rise is accompanied by an increase in variability, the frequency of warm days is even greater, which has been described as a consequence of global climate change (Folland et al. 2001). This is what happens at the stations below the inversion layer on both windward and leeward slopes. The slightly different behaviour in the high mountain indicates that the climate system there is different from the rest of the island. Above the temperature inversion, the climate is greatly influenced by the large-scale circulation, while below it, especially in the north, the climate is more affected by local circulation where proximity to the sea and trade winds play a greater part. The oceanic influence is noted from the reduced warming in coastal compared to mid-altitude areas, both windward and leeward, while the importance of the trade-winds is evident from the greater warming on windward than leeward slopes. This is in line with the arguments of Pepin and Lundquist (2008) regarding cloudy and windy areas where advection plays a significant role in climate, and in general, the lower the mean temperature of the sector, the greater the warming.

It remains to be seen to what extent the observed warming may be due to urban 'heat islands', derived from the increased building development Tenerife has undergone in recent decades at coastal altitudes up to 400 m. Two factors contribute to downplaying the potential impact of such warming: 1) the fastest growing urban areas are precisely those that show least warming, possibly due to their nearness to the sea and the good ventilation provided by the trade winds, minimizing the heat-island effect, and 2) except for station C449C (Santa Cruz), all the other readings come from natural or rural areas, where the increase of temperature due to urban growth is less likely.

On comparing our data with the Global Historical Climate Network reference series (GHCN) of the NASA Goddard Institute for Space Studies[1] (GISS) for land stations only in the northern hemisphere, warming on Tenerife was 35% lower in the period 1944–2010, and

[1] http://data.giss.nasa.gov/gistemp/

almost 40% lower in the period 1970–2010. Below the inversion layer, warming is even less and on the leeward side it is half that estimated by the GISS model. In the high mountain areas, however, warming appears to be quite similar to the global trend.

The warming observed on Tenerife is only slightly lower than the combined land-ocean temperature index (LOTI) of the GISS model for the northern hemisphere, and similar to LOTI for latitudes 24º–44ºN. Our data show that warming was higher than the estimates by GISS at stations above the inversion, similar at windward stations below the inversion, and a little lower at leeward stations below it.

The data from purely oceanic stations of the National Centers for Environmental Prediction (NCEP) reanalysis monthly means,[2] produced at NOAA/ESRL PSD from one location to the north of Tenerife (28.5–29.5 N/17–16 W) and other to the south (26.5–27.5 N/16–15 W), indicate only very slightly higher warming over the period 1948–2010 than that observed on the island below the sea of clouds.

5 Conclusion

Our analysis suggests a clear pattern in the annual temperature trends on Tenerife. On the one hand, the overall warming is milder on the island than the average for the northern hemisphere, and is closer to that associated with sea-surface records in the Canaries. On the other, it is stronger in the high mountain areas where the climate is predominantly governed by the global circulation system, than in mid-altitude and coastal sectors where the climate system is highly influenced by the ocean and the trade winds.

Global warming on Tenerife is reflected mainly in an asymmetric increase of minimum temperatures, most clearly seen on northern slopes. As a result, the DTR has tended to decrease, particularly on the windward side (attributable to increased cloudiness as the most plausible hypothesis), but less apparently on leeward slopes (although statistically significant), where it is probably influenced by warming of the sea surface.

There should be further analysis of variations in the frequency, intensity and direction of the trade winds and how this is influencing the formation of the stratocumulus clouds on the northern side of the island. Future studies will focus our work towards the trends in monthly temperatures, and their importance for climate, particularly in the development and structure of terrestrial ecosystems, as shown by the preliminary study by Sperling et al. (2004). Tenerife is home to a unique biodiversity of great value, much of which is directly linked to the survival of the cloud-dependent laurel forest, thus changes in the frequency, intensity and seasonality of this stratocumulus cover may have a strong influence on its conservation.

Acknowledgements Our research is part of studies undertaken for the project ClimaImpacto MAC/3/C159 within the transnational cooperation programme of the European Union MAC 2007–2013, led by the Canary Island Agency for Sustainable Development and Climate Change. The authors wish to express their gratitude to the Canary Islands department of the State Meteorological Agency of Spain (AEMET) for the provision of basic climate information, to Enric Palle from the "Instituto de Astrofísica de Canarias" for his suggestions on the original manuscript and to G. Jones for his assistance with the English text. The thoughtful comments of three anonymous referees, leading to significant improvements of this paper, are also gratefully acknowledged.

[2] http://www.esrl.noaa.gov/psd/data/timeseries/

References

Aguilar E, Auer I, Brunet M, Peterson TC, Wieringa J (2003) Guidelines on climate metadata and homogenization. WCDMP Guidelines Series, WMO/TD nº 1186, P Llansó (ed.), 50 pp., Geneva

Alexandersson HA (1986) A homogeneity test applied to precipitation data. J Climatol 6:661–675

Alexandersson H, Moberg (1997) A homogenization of Swedish temperature data. Part I: homogeneity test for linear trends. Int J Climatol 17:25–34

Andreae MO, Jones CD, Cox PM (2005) Strong present-day aerosol cooling implies a hot future. Nature 435:1187–1190

Braganza K, Karoly DJ, Arblaster JM (2004) Diurnal temperature range as an index of global climate change during the twentieh century. Geophys Res Lett 32:L13217. doi:10.1029/20046L019998

Brunet M, Jones PD, Sigro J, Daladié O, Aguilar E, Moberg A, Della-Marta PM, Lister D, Walther A, López D (2007) Temporal and spatial temperature variability and change over Spain during 1850–2005. J Geophys Res 112:D12117. doi:10.1029/2006JD008249

Costa AC, Soares A (2009) Homogenization of climate data: review and new perspectives using geostatistics. Math Geosci 41:291–305

Dai A, Trenberth KE, Karl TR (1999) Effects of clouds soil moisture, precipitation and water vapor on diurnal temperature range. J Climate 12:2451–2473

Diaz HF, Bradley RD (1997) Temperature variations during the last century at high elevation sites. Clim Change 36:253–279

Dorta P (1996) Las inversiones térmicas en Canarias. Investigaciones geográficas 15:109–124

Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Folland CK (1997) A new look at maximum and minimum temperature trends for the globe. Science 277:364–367

Folland CK, Karl TR, Christy JR, Clarke RA, Gruza GV, Jouzel J, Mann ME, Oerlemanns J, Salinger MJ, Wang S-W (2001) Observed climate variability and change. In: Houghton JH, Ding Y, Griggs DJ, Noguer M, van der Linder PJ, Dai X, Maskell K, Johnson CA (eds) "The scientific basis—contribution of working group I to the third assessment report of the intergovernmental panel on climate change". Cambridge Univ. Press, New York, pp 99–181

Font I (1956) El Tiempo Atmosférico en las Islas Canarias. Servicio Meteorológico Nacional (INM), Serie A (memoria No. 26). 95 pp.

Giambelluca TW, Diaz HF, Luke MSA (2008) Secular temperature changes in Hawai'i. Geophys Res Lett 35: L12702. doi:10.1029/2008GL034377

Guttman NB, Quayle RG (1990) A review of cooperative temperature data validation. J Atmos Oceanic Technol 7:334–339

Hu Y, Fu Q (2007) Observed poleward expansion on the Hadley circulation since 1979. Atmos Chem Phys 7:9367–9384

Jensen MP, Vogelmann AM, Collins WD, Zhang GJ, Luke EP (2008) Investigation of regional and seasonal variations in marine boundary layer cloud properties from MODIS observations. J Climate 21:4955–4973

Jones PD (1994) Hemispheric surface air temperature variations: a reanalysis and an update to 1993. J Climate 7:1794–1802

Jones PD, Hulme M (1996) Calculating regional climatic time series for temperature and precipitation: methods and illustrations. Int J Climatol 16:361–377

Jones P, Wigley T, Kelly P (1982) Variations in surface air temperatures: part 1. Northern hemisphere, 1881–1980. Mon Wea Rev 110(2):59–70

Jones PD, Parker DE, Osborn TJ, Briffa KR (2011) Global and hemispheric temperature anomalies –land and marine instrumental records. In trends: a compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn, USA. doi:10.3334/CDIAC/cli.002

Khaliq MN, Ouarda T (2007) On the critical values of the standard normal homogeneity test (SNHT). Int J Climatol 27:681–687

Klein SA, Hartmann DL (1993) The seasonal cycle of low stratiform clouds. J Climate 6:1588–1606

Levene H (1960) Robust tests for equality of variances. In: Olkin I, Hotelling H et al. (eds) "*Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling*", Stanford University Press. 278–292 pp.

Liepert BG (2002) Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. Geophys Res Lett 29(10):1421. doi:10.1029/2002GL014910

Loope LL, Giambelluca TW (1998) Vulnerability of island tropical montane cloud forests to climate change, with special reference to East Maui, Hawaii. Clim Change 39(2–3):503–517

Marzol MV (2001) El Clima. In: Fernández-Palacios JM, Martín-Esquivel JL (eds) "Naturaleza de las Islas Canarias. Ecología y conservación". Publicaciones Turquesa, S/C de Tenerife, pp 87–93

Oñate JJ, Pou A (1996) Temperature variations in Spain since 1901: a preliminary analysis. Int J Climatol 16:805–815

Osborn TK, Briffa KR, Jones PD (1997) Adjusting variance for sample-size in tree-ring chronologies and other regional mean time series. Dendrochronologia 15:89–99

Pepin NC, Lundquist JD (2008) Temperature trends at high elevations: patterns across the globe. Geophys Res Lett 35:L14701. doi:10.1029/2008GL034026

Pepin NC, Norris JR (2005) An examination of the differences between surface and free-air temperature trend at high-elevation sites: relationships with cloud cover, snow cover, and wind. J Geophys Res 110: D24112. doi:10.1029/2005JD006150

Peterson TC, Vose R, Schmoyer R, Razuvaev V (1998) Global historical climatology network (GHCN) quality control of monthly temperature data. Int J Climatol 18:1169–1179

Petit J, Prudent G (2008) Climate change and biodiversity in the European union overseas entities. UICN, Brussels, p 178

Pettitt AN (1979) A nonparametric approach to the change-point problem. Appl Statist 28:126–135

Reeves J, Chen J, Wang XL, Lund R, Lu Q (2007) A review and comparison of changepoint detection techniques for climate data. J Appl Meteor Climatol 46:900–915

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421:57–60

Sanroma E, Palle E, Sánchez-Lorenzo A (2010) Long-term changes in insolation and temperatures at different altitudes. Environ Res Lett 5:1–6

Santer BD, Wigley TML, Boyle JS, Gaffen DJ, Hnilo JJ, Nychka D, Parker DE, Taylor KE (2000) Statistical significance of trends and trend differences in layer-average atmospheric temperature time series. J Geophys Res 105(D6):7337–7356

Seidel DJ, Fu Q, Randel WJ, Reichler TJ (2008) Widening of the tropical belt in a changing climate. Nat Geosci 1(1):21–24

Smith SJ, van Aardenne J, Klimont Z, Andres RJ, Volke A, Delgado S (2011) Anthropogenic sulfur dioxide emissions: 1850–2005. Atmos Chem Phys 11:1101–1116

Sneyers R (1975) *Sobre el análisis estadístico de las series de observaciones*. OMM, Nota técnica 143. OMM-Nº 415. Geneva.

Sperling FN, Wasingthon R, Wittaker RJ (2004) Future climate change of the subtropical north Atlantic: implications for the cloud forests of Tenerife. Clim Change 65(1–2):103–123

Stepanek P (2007) AnClim—*software for time series analysis (for Windows)*. Dept. of Geography, Fac. of Natural Sciences, Masaryk University, Brno. 1.47 MB.

Stone DA, Weaver AJ (2002) Daily maximum and minimum temperature trends in a climate model. Geophys Res Lett 29(9):1356, GL014556

Stone D, Weaver A (2003) Factors contributing to diurnal temperature range trends in twentieth and twenty-first century simulations of the CCCma coupled model. Clim Dynamics 20:435–445

Stott PA, Huntingford C, Jones CD, Kettleborough JA (2008) Observed climate change constrains the likelihood of extreme future global warming. Tellus 60(1):76–81

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) "Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change". Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Trueman M, d'Ozouville N (2010) Characterizing the Galapagos terrestrial climate in the face of global climate change. Galapagos Res 67:26–37

Venema VKC, Mestre O, Aguilar E, Auer I, Guijarro JA, Domonkos P, Vertacnik G, Szentimrey T, Stepanek P, Zahradnicek P, Viarre J, Müller-Westermeier G, Lakatos M, Williams CN, Menne M, Lindau R, Rasol D, Rustemeier E, Kolokythas K, Marinova T, Andresen L, Acquaotta F, Fratianni S, Cheval S, Klancar M, Brunetti M, Gruber C, Prohom Duran M, Likso T, Esteban P, Brandsma T (2011) Benchmarking monthly homogenization algorithms. Climate of the Past Discussions 7(4):2655–2718

Weber RO, Talkner P, Stefanicki G (1994) Asymmetric diurnal temperature change in the alpine region. Geophy Res Lett 21(8):673–676

Wild M (2009) Global dimming and brightening: a review. J Geophys Res 114:D00D16. doi:10.1029/2008JD011470

WMO (1996) *Climatological normals (CLINO) for the period 1961–1990*. Geneva, Pub. 847, 768 pp.

Yue S, Hashino M (2003) Temperature trends in Japan: 1900–1996. Theor Appl Climatol 75:15–27