INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **34**: 604–622 (2014)
Published online 16 May 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3710

An analysis of the climate of Macaronesia, 1865–2012

T. E. Cropper* and E. Hanna
Department of Geography, University of Sheffield, Sheffield, UK

ABSTRACT: New monthly, long-running, continuous surface air temperature records for four island chains throughout the Macaronesian biogeographical zone in the North Atlantic Ocean are presented. The records run from 1865 for the Azores and Madeira, 1885 for the Canary Islands and 1895 for Cape Verde. Recent (1981–2010) warming across these islands is significant in summer (JJA) for the Canary Islands, Cape Verde and Madeira, ranging from 0.40 to 0.46 °C per decade. Annually, the temperature trends across this period range from 0.30 to 0.38 °C per decade across all four island chains (significant for all but the Canary Islands), which exceed the station-based, average global temperature rise by up to 0.10 °C per decade. Precipitation records from multiple islands across Macaronesia are also presented in addition to sea-level pressure records from the Azores and Cape Verde. Cape Verde wet season (ASO) precipitation is found to have significantly increased at two of our three sites from 1981 to 2010. The Azores, Canary Islands and Madeira precipitation trends display no significant changes, although the three Azores stations display a recent positive tendency. The extended Azores pressure record allows us to construct an entirely station-based Azores-Iceland North Atlantic Oscillation index (NAOI) from 1865 to 2012 and extend the daily station-based index back to 1944, further than the longest previous daily NAOI by 6 years. In addition, we use the sea-level pressure difference between the Azores and Cape Verde to create a novel method of characterizing trade wind strength across Macaronesia, the Trade Wind index (TWI), which points towards a recent, statistically significant increase (since 1973) throughout the region. Links between the winter and summer NAOI, TWI and Macaronesian temperature and precipitation are explored, as are the differences in warming trends between Macaronesia and analogous subtropical island chains, most of which are found to be warming at slower rates than the Macaronesia stations.

KEY WORDS Macaronesia; climate reconstruction; Sen slope; Mann–Kendall; North Atlantic Oscillation; trade winds

Received 7 December 2012; Revised 15 February 2012; Accepted 3 April 2013

1. Introduction

Macaronesia, the 'Islands of the Fortunate' (Figure 1), is the name for the climatologically critical region of the North Atlantic Ocean that encompasses the Azores, Canary Islands, Cape Verde, Madeira and the Savage Islands. The climate of Macaronesia is influenced by the semi-permanent Azores high-pressure system, prevailing north-easterly trade winds, and the surrounding ocean including the Azores and Canary Currents. In addition, the abrupt altitudinal range and contrast of the numerous islands across these archipelagos, and their isolation from the mainland, result in climates that are atypical for their respective latitudes (Martín *et al.*, 2012).

The sea-level pressure (SLP) time series from the meteorological station at Ponta Delgada, Azores, is crucial in calculation of the station-based North Atlantic Oscillation index (NAOI; Hurrell, 1995): a teleconnection with wide-ranging climatological influences across much of Western and Central Europe (Hurrell and Deser, 2009). In addition to this long-running SLP time series, monthly mean air temperature and precipitation data are also available since 1865 for Madeira and the Azores, 1880 for the Canary Islands and 1895 for Cape Verde. Despite this abundance of available data for a climatically important region, it is surprising that a collective report of the climate of Macaronesia is lacking in any English-language journal, given the comparative interest in Icelandic climate at the opposite node of the NAO (Jónsson and Gardarsson, 2001; Hanna *et al.*, 2004, 2006; Jónsson and Hanna, 2007). It is also noteworthy that the region was excluded from the 'Small Island' section of the Intergovernmental Panel on Climate Change AR4 (WG1, 11.9, p. 909–917; Christensen *et al.*, 2007). To combat this unfortunate lack of attention, we report some of the significant available Macaronesian instrumental climate records and discuss and analyse these with regards to current global climate change. We additionally present: (1) an extended daily (1944 to present), and monthly (1865 to present) station-based NAOI, based on the reconstructed Azores SLP data; and (2) a novel index for characterizing trade wind strength across the Macaronesian archipelagos.

For the purpose of this paper, Macaronesia will refer to the four island chains of the Azores, Canary Islands, Madeira and Cape Verde (Figure 1). The Savage Islands are predominantly uninhabited and have no long-term meteorological records. Previously published Macaronesian climate data are sparse. Early interest in

* Correspondence to: T. E. Cropper, Department of Geography, University of Sheffield, Winter Street, Sheffield S10 2TN, UK. E-mail: ggp10tec@shef.ac.uk

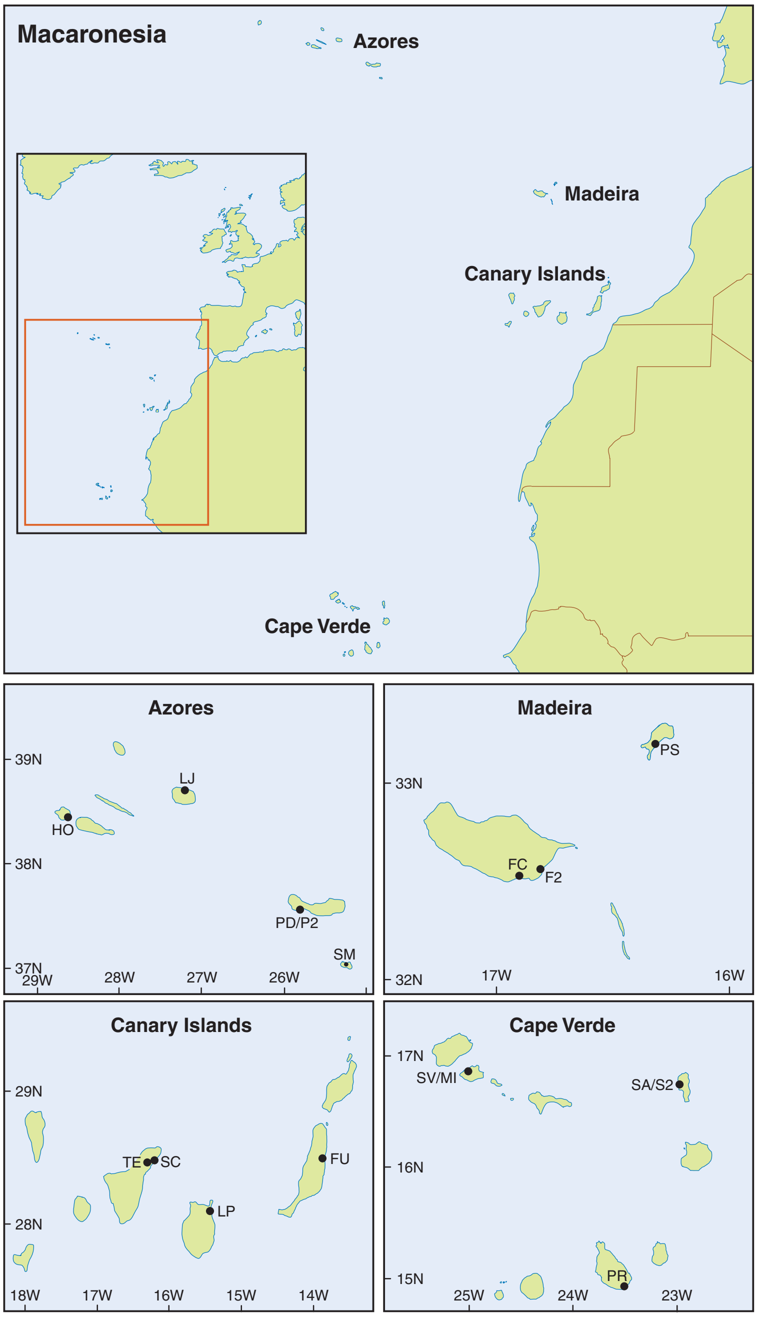

Figure 1. Map of the Macaronesian region illustrating its location within the North Atlantic Ocean. The Azores (top left), Canary Islands (bottom left), Madeira (top right) and Cape Verde (bottom right) island chains are enhanced and marked with the meteorological stations used in this article (Table 1).

the region can be traced back to Harris *et al.* (1961) who reported the characteristics of semi-diurnal oscillations in temperature, wind and pressure at Terceira, Azores. More recently, Tomé and Miranda (2004) identified a 0.22 °C per decade increase of maximum December temperature from 1960 to 2002 at Angra do Heroismo, Azores, with Santos *et al.* (2004) reporting a 0.30 °C per decade increase in maximum (annual) temperature at the same location for 1963–2003. The latter study also identified a significant increase in maximum (0.53 °C per decade) and minimum (0.66 °C per decade) temperatures at Funchal, Madeira, for 1973–2003.

Sperling *et al.* (2004) observed a significant summer (JJA) temperature increase of 0.16 °C per decade at Izana, Canary Islands, for 1950–1999 (rising to 0.45 °C per decade for 1970–1999) in addition to significant summer temperature trends at La Laguna and Santa Cruz (all on the central island of Tenerife). More recently, Martín *et al.* (2012) using an aggregate of 28 stations, observed a 0.17 °C per decade mean temperature rise for 1970–2010 across Tenerife, mainly due to increasing minimum temperatures. Winter precipitation trends across the western and central Canary Islands are negatively linked to the NAO (García-Herrera *et al.*, 2001), with decreasing trends in precipitation during the second half of the twentieth century a function of a reduction in the occurrence and intensity of extreme events (García-Herrera *et al.*, 2003). For Cape Verde, McSweeney *et al.* (2010) identified a mean annual temperature increase of 0.14 °C per decade, with a stronger increase of 0.23 °C per decade present across the wet (ASO) season. Significant precipitation trends were absent, although they noted a recent increase in precipitation during the drier (NDJ) season (in particular, the high values displayed in 1999, 2000 and 2002). A recent climate atlas (Climate Atlas, 2012) documents the background of observation history and annual cycles of temperature and precipitation across the Azores, Canary Islands and the Madeira.

In the following we first introduce the key datasets and methods that we use for analysing Macaronesian climate change. Next we discuss the creation of the NAOI and Trade Wind (TWI) indices and their widespread recent (1981–2010) effects on Macaronesia climate, followed by analysis of the long-term temperature and precipitation records. We then relate the recent temperature trends in Macaronesian climate to broadly analogous island sites across both hemispheres and briefly consider the nature of the long-term (multidecadal) oscillating relationship between the islands' temperature and the NAOI.

2. Methodology

2.1. Data, processing and homogeneity

Macaronesian climate data were extracted from several sources (Table 1). Data were obtained from the Global Historical Climatological Network version 3 (GHCN, Lawrimore *et al.*, 2011), the European Climate Assessment and Dataset (ECA; Klein Tank *et al.*, 2002), the National Climatic Data Centre's Global Summary of the Day (GSOD) network (ncdc.noaa.gov) and the Annual to Decadal Variability in Climate in Europe (ADVICE) pressure archive (Jones *et al.*, 1999). In addition to the quality control procedures each of these data sources undergo, we apply four tests of homogeneity to ensure robust quality of data. These are the standard normal homogeneity test (SNHT; Alexanderson, 1986), Pettitt test (Pettitt, 1979), Buishand range test and Von Neumann ratio (Buishand, 1982). The SNHT and Buishand tests assume a normal distribution, whereas the Pettitt and the Von Neumann ratio do not require this assumption (Costa and Soares, 2009). We also plot the moving average of the variance as well as visually examining the raw time series to assist in identifying inhomogeneities. Station metadata are limited, but considered when available. The SNHT, Buishand range and Pettitt test all have a H_0 (null hypothesis) of independent, identical distribution and a H_1 (alternative hypothesis) of a stepwise shift in the mean (Wijngaard *et al.*, 2003) and are location-specific, with the SNHT more suited to identifying breaks near the start or end of a time series and the Buishand and Pettitt tests more sensitive to shifts in the middle. Significance tests (at 1%) for each homogeneity test are calculated using 10 000 Monte Carlo simulations (Wilks, 1995). For further robustness, the homogeneity tests are carried out on the raw monthly values in addition to the annual (January to December) values for each station, as well as alternative time-frames when required for suspect stations (Martín *et al.*, 2012) to further elucidate and identify potential breaks. The GHCN v3 records were also compared with the previous records from the earlier version of the GHCN (version 2; Peterson and Vose,

Table 1. Summary of meteorological stations and data products utilized in this study.

Station	Identification	Island chain	Latitude (North)	Longitude (East)	Altitude (m)	Highest Island elevation (m)	Start	End	Source
Ponta Delgada	PD	Azores	37°70′	334°30′	67	1105	1865	2003	GHCN, ADVICE
Ponta Delgada Daily	P2	Azores	37°73′	334°30′	71	1105	1973	2012	GSOD
Santa Maria	SM	Azores	37°00′	334°88′	100	587	1944	2005	GHCN, GSOD
Lajes	LJ	Azores	38°77′	332°90′	55	886	1947	2012	GSOD
Horta	HO	Azores	38°50′	331°40′	62	1043	1902	2008	GHCN, GSOD
Tenerife	TE	Canary Islands	28°47′	343°68′	617	3718	1885	2012	GHCN
Tenerife	TE	Canary Islands	28°47′	343°68′	617	3718	1960	2012	ECA
Santa Cruz De Tenerife	SC	Canary Islands	28°45′	343°75′	36	3718	1881	2012	GHCN
Santa Cruz De Tenerife	SC	Canary Islands	28°45′	343°75′	36	3718	1938	2012	ECA
Las Palmas	LP	Canary Islands	28°10′	344°58′	25	1949	1887	2012	GHCN
Las Palmas	LP	Canary Islands	28°10′	344°58′	24	1949	1960	2012	ECA
Fuerteventura	FU	Canary Islands	28°44′	346°14′	25	807	1970	2012	ECA
Sal	SA	Cape Verde	16°73′	337°05′	55	406	1951	1996	GHCN
Sal Daily	S2	Cape Verde	16°73′	337°43′	54	406	1973	2012	GSOD
Mindelo	MI	Cape Verde	16°88′	335°00′	63	725	1884	1961	GHCN
Saint Vincent	SV	Cape Verde	16°85′	335°00′	2	725	1883	1976	GHCN
Praia	PR	Cape Verde	14°90′	336°48′	35	1394	1921	1960	GHCN
Funchal	FC	Madeira	32°63′	343°10′	50	1862	1865	2012	GHCN, ADVICE
Funchal Daily	F2	Madeira	32°68′	343°23′	49	1862	1973	2012	GSOD
Porto Santo	PS	Madeira	33°07′	343°65′	82	402	1940	2004	GHCN

Refer to main text for dataset descriptions and reference. The Identification column indicates the labels used in Figure 1.

1997). Our aim was to ultimately disturb the historical records as little as possible, only applying corrections when deemed necessary (Section 3).

To create a climatological time series of suitable quality for the analysis for each island chain, we first applied the homogeneity tests in an 'absolute' manner (Aguilar *et al.*, 2003) to each individual station. We additionally considered the temporal coverage and completeness of the stations when deciding on a 'reference-series' for each island chain, on which the final time series were to be based. The absolute method is a test of the station against time, where the main caveat is that identified break points are difficult to interpret without metadata; however, it is necessary in our analysis to delineate our 'reference station' and that is why we employ the less statistically powerful running variance analysis (Box, 2002) and visual interpretation to aid in our interpretation of break points. When a break point is identified, one of three outcomes may occur:

1. 'False-positive' – a break point is identified but determined to be a realistic climate variation.
2. 'Quotient correction' – a break point is identified and there is an obvious 'shift'; adjustment is made by the difference in mean between the periods of inhomogeneity.
3. 'Gradual correction' – a break/change point is identified as a slowly evolving function over time as opposed to dramatic shift. Here the period of inhomogeneity will have its linear trend removed (with the slope calculated from the trend of the homogenous time period or the slope of the reference station when using the 'relative' homogeneity approach). This would usually be applicable when a station location has undergone a slowly evolving change over time (i.e. land use change) or a trend occurs in a station that is not reflected in 'reliable' neighbouring ones.

After a reference station for the Azores, Canary Islands, Madeira and Cape Verde were identified and adjusted if needed, 'relative' homogeneity tests were applied between nearby stations and the reference station to assess the suitability of the nearby stations that were used in the regression splicing for creating complete time series (Section 2.2.). The reference stations are selected on the basis of the similarity of physical attributes [location, altitude, exposure, orientation/aspect (i.e. which side of the island)] and statistical (mean, standard deviation, ranges, distributions) characteristics. The relative homogeneity method has the advantage of isolating non-climatic factors (Cao and Yan, 2012), under the assumption that the proximity of stations is such that their true signals both reflect the same climate.

2.2. Regression splicing

The following approach is used in creation of the temperature time series for each island and the SLP time series for the Azores and Cape Verde. Hanna *et al.* (2006, 2008) utilize the regression relationship between nearby meteorological stations in their reconstructions of, respectively, a sea-surface temperature record for Iceland and a pressure variability record for the Channel Islands. Here, we adopt a similar approach as even our 'reference-series' for each Macaronesian island chain is plagued by gaps to a certain degree (Table 1), and needs extending either further backwards or forward in time. We aim to complete gaps in the reference series by regression with the most suitable nearby station (in terms of the physical and statistical characteristics earlier mentioned, and the timespan of data). The regression equation is:

$$y = mx + c \tag{1}$$

where y is the dependent meteorological time series (the 'reference-station' with gaps), x is the meteorological time series being used to plug the gaps, with c as a constant and m is the change in y as a function of x. For our regressions we use the Thiel-Sen slope estimator (Jain and Kumar, 2012). In this formula, the slopes (T_i) of all data pairs are calculated as:

$$T_i = \frac{x_j - x_k}{j - k} \text{ for } i = 1, 2, \ldots, N \tag{2}$$

where x_j and x_k are data values at time j and k (where $j > k$) respectively. This results in a number of slopes (N_p) based on the number of data pairs (n):

$$N_p = n\,(n-1)\,/2 \tag{3}$$

then, the slopes are sorted and ranked from lowest to highest and the median value is selected as m in the linear regression. The constant c is defined as (Granato, 2006):

$$c = Y_{\text{median}} - mX_{\text{median}} \tag{4}$$

For creating regression relationships between the various meteorological stations, we take the original Thiel-Sen slope model, remove the data pairs associated with residuals that are $\geq \pm 1.96\sigma$ about the mean value of residuals and recalculate the regression. We then use the modified regression relationship to fill in the gaps in the reference time series for each island and extend the record as far backwards and forwards in time as possible, based on the available data. If this still results in gaps, single months are filled by the mean of the adjacent two months and longer gaps are set to the average monthly value of the previous and subsequent five years for each month. This causes minimal disturbances to the long-term trend and is only used to fill a small minority of gaps (6/1770 monthly cases for the Azores record and 4/1531, 19/1459 and 6/1772 for the Canary Islands, Cape Verde and Madeira records respectively).

We also use the Thiel-Sen slope estimator to quantify linear trends elsewhere in the article. To ascertain the significance of linear trends we use the non-parametric

Mann–Kendall test. The Kendall's statistic (S) is (Salas, 1993):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}\left(x_j - x_k\right) \tag{5}$$

where n is the number of data points, x_j and x_k are values from time j and k respectively and sgn$(x_j - x_k)$ is computed as:

$$\text{sgn}\left(x_j - x_k\right) = \begin{cases} 1, \text{if } x_j - x_k > 0 \\ 0, \text{if } x_j - x_k = 0 \\ -1, \text{if } x_j - x_k < 0 \end{cases} \tag{6}$$

with $n > 10$, the Kendall's statistic is approximately normally distributed such that its mean, E, and variance, σ_s, are summarized as:

$$E\,(S) = 0 \tag{7}$$

$$\sigma_s = \sqrt{\frac{n\,(n-1)\,(2n+5) - \sum_{i=1}^{q} t_i\,(i)\,(i-1)\,(2i+5)}{18}} \tag{8}$$

where q is the number of tied groups, and t_i the number of data values in the ith tied group. From this, the test statistic (Z) can be summarized as:

$$Z = \begin{cases} \frac{s-1}{\sqrt{\sigma(s)}} \text{ if } S > 0 \\ 0 \text{ if } S = 0 \\ \frac{s+1}{\sqrt{\sigma(s)}} \text{ if } S < 0 \end{cases} \tag{9}$$

where a positive (negative) Z value indicates an increasing (decreasing) trend. The test H_0 is that there is no trend in the series; the H_1 is a trend over time. A two-tailed test at α level of significance rejects the H_0 if:

$$|Z| > Z_{1-\alpha/2} \tag{10}$$

where $Z_{1-\alpha/2}$ is obtained from standard normal distribution tables (Drápela and Drápelová, 2011). We use $\alpha = 90$, 95 and 99% in this investigation. We also apply the modified Mann–Kendall test using two different methodologies (Hamed and Rao, 1998; Yue and Wang, 2002) to account for the effect of autocorrelation, and only report significant trends that pass all three (the standard and two modified) Mann–Kendall tests.

2.3. Precipitation Infilling

For precipitation, where possible, we report trends for each individual island across each island chain. This is because precipitation is far more variable across islands than temperature, i.e. there is a distinct contrast between western and eastern Canary Island precipitation regimes (García-Herrera *et al.*, 2003) and the differences between Madeira (island) and Porto Santo in the Madeiran island chain are pronounced. This variability is influenced by location (the western islands being closer to the path of the storm tracks associated with the Azores high) and altitude (the eastern Canary Islands and Porto Santo are much flatter islands, so receive much less precipitation than their counterparts). We aim to disturb the historical precipitation records as little as possible after tests for normality, with monthly gaps set to the long-term average for the month of the same name. This method has been used previously (Zhang *et al.* 2011a, 2011b) and whilst it does not impact the overall long-term trends, it potentially leads to increased precipitation amounts for certain islands that typically have no precipitation across a number of months: in particular for Porto Santo (Madeira) and the Canary Islands and Cape Verde. Therefore for gap-filling across typically 'dry' months: e.g. March to July for Cape Verde stations, where the average monthly values are below 1 mm, we set the value to 0.

2.4. Additional methods

All original daily records are averaged or aggregated to the monthly scale when required, only months with >80% of their daily data for temperature and SLP and 100% of their data for precipitation were considered. Our NAO and Trade Wind indices (Section 3.2.) are created by the normalized pressure differences (the monthly anomaly divided by the long-term standard deviation) between the Azores and, respectively, Iceland and Cape Verde. We use Fourier spectral analysis and wavelet analysis (Torrence and Compo, 1998). We additionally use these following datasets – the National Centers for Environmental Prediction/Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay *et al.*, 1996), the ERA-Interim reanalysis (ERA-I, Dee *et al.*, 2011) and the twentieth century (20CR) reanalysis (Compo *et al.*, 2011) – to support the station-based results.

3. Results

3.1. Pressure

We extend the monthly Azores SLP record from Ponta Delgada (which stopped continuously reporting in 2003) by regression against a daily Ponta Delgada station (Table 1). We also, by regression of the daily Ponta Delgada station against stations at Lajes and Santa Maria (Figure 1, Table 1), extend the daily Azores SLP record back to 1944. This allows us to extend the daily, station-based NAOI further back in time than has been done before, from 1944 to 2012, whereas previously the daily NAO has been extended back to 1950 by the Climate Prediction Centre (www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml). Since 2003, Hurrell's station-based Azores-Stykkisholmur/Reykjavik NAO has had to substitute the Ponta Delgada time series with that of the nearest NCEP/NCAR grid box (climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-station-based). The extension of the Azores SLP record here negates the reason to do that and so a purely station-based NAO spanning 1865–2012 is presented (Figure 2): the correlation of its monthly means with the Hurrell (1995) NAO index remains high at $r = 0.99$ for 2004 to June 2012 (since the

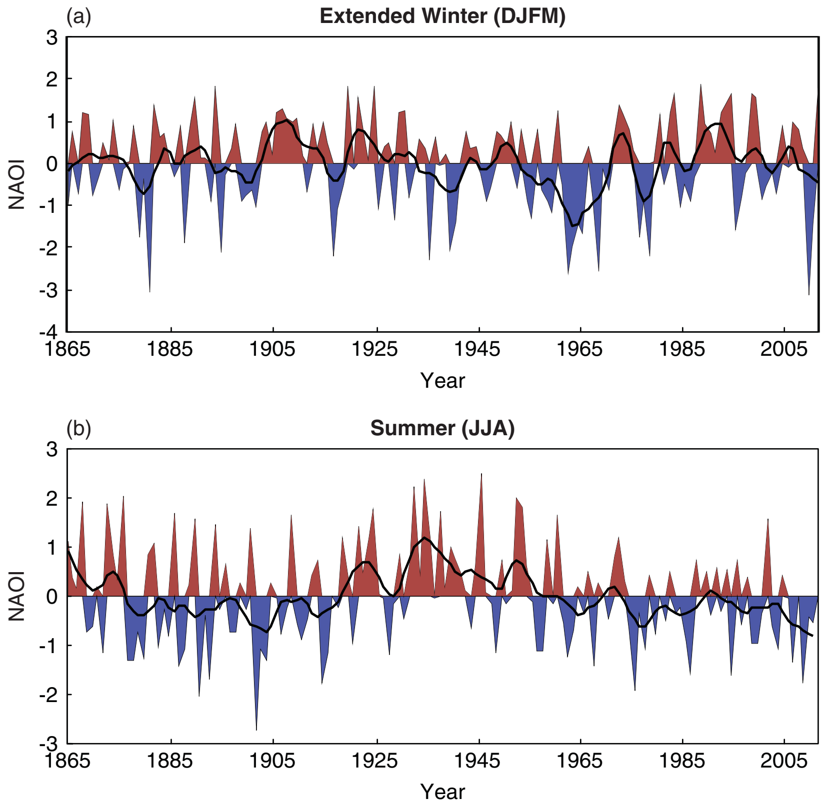

Figure 2. The station-based, (a) extended winter (DJFM) and (b) summer (JJA) North Atlantic Oscillation index 1865–2012. The northern station is a combination of Stykkisholmur/Reykjavik SLP record, and the southern station is our extended Ponta Delgada SLP record. Black lines illustrate an 11-year LOESS filter.

Azores station was replaced) although our wholly station-based NAOI is clearly more self-consistent. The advantage in using Ponta Delgada as the southern station is that it is a better representation of the oscillation across the entire year in comparison to using Gibraltar or Lisbon as the southern station. However, the station-based NAOIs (particularly Gibraltar or Lisbon based) may not suitably capture the high summer (July to August) variability, as the pattern is typically shifted northeast to a British Isles-Greenland seesaw instead of the Azores-Iceland pattern during these 2 months (Bladé *et al.*, 2012). This potentially makes the Azores-Iceland NAOI slightly less optimal across these 2 months, but for Macaronesia, it will still be an adequate representation of the strength of the Azores High, making it useful for studying climate across the region. Our extended winter (DJFM) and summer (JJA here, as opposed to the typical JA 'high' summer classification as the stations are spatially fixed) NAOI (Figure 2) show the important (multi-)decadal oscillations that have had profound effects upon European climate (Hurrell, 1995). Of particular note are the 1980–1990s shift to a predominantly positive phase of the (winter) NAO and the recent tendency towards negative values [8 of the last 12 years (2001–2012) have been negative NAOI winters]. The impacts of the NAO have been linked to climate variables across a wide spatial range, therefore, any shift or a trend to more extreme values will have significant climate impacts, particularly on extreme events (Scaife *et al.*, 2008). For example, the exceptional 2009–2010 negative winter NAOI contributed to unusually high SST's across Macaronesia, which led to severe flooding across Madeira and the Canary Islands (Ball, 2011); only the 1881 DJFM value is lower in the record. The summer NAOI displays a long-term negative trend which starts in the 1940s (Figure 2(b)) and switches to predominantly negative values around 1975. This 'shift' is concurrent with one observed in the late 1970s by Sun *et al.* (2008). On the contrary, the summer NAOI has been predicted to shift to its positive phase in various climate predictions (Hu and Wu, 2004; Bladé *et al.*, 2012); yet its recent (last 10–15 years) trend has been increasingly negative, regardless of which NAOI is used (either the Azores/Gibraltar – Iceland station based or the principal component-based approach of the CPC or the first principal component of an empirical orthogonal analysis of SLP across 25–70°N, 70°W–50°E, not shown). Impacts of the NAOI on Macaronesian climate are discussed in Sections 3.2., 3.3. and 4.

The longest station-based SLP record for Cape Verde is from Sal (1973–2012, Table 1). The Azores and Cape Verde SLP monthly records are typically poorly correlated (1973–2012, $r = 0.15$). However, their respective positions and the distance between them [approximately 2400 km (Figure 1)] mean that analysis of the pressure difference between them may yield a realistic proxy index for the strength of the trade winds. Characterizing trade

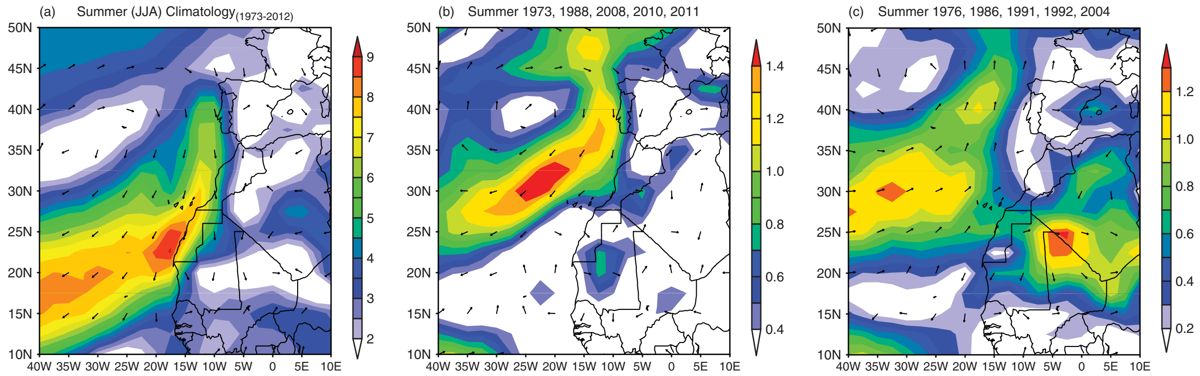

Figure 3. (a) The summer (JJA) climatological mean wind speed (m/s) and vectors across the Macaronesian region for 1973–2010 (from the NCEP/NCAR reanalysis) and the composite anomaly of the five (b) most positive and (c) negative years for the summer TWI. Images downloaded from and copyrighted to the NOAA/ESRL Physical Sciences Division, Boulder Colorado (http://www.esrl.noaa.gov/psd/).

wind strength is important in determining the strength of coastal upwelling off northwest Africa (Hagen, 2001) and is important for the orographic uplift that characterizes island rainfall (Section 3.3.). Recently, it appears increasingly likely that apparent positive trends in meridional wind speeds from observation-based datasets are contaminated with a positive trend associated with increased ship sizes, which leads to overestimated (Bakun *et al.*, 2010) or even reversed trends (Tokinaga and Xie, 2011). Using SLP from island meteorological stations should minimize any potential contamination. Our TWI is calculated as the normalized pressure between the Azores and Cape Verde. A positive (negative) value is equivalent to a stronger (weaker) difference in SLP pressure between the two sites, in theory equating to stronger (weaker) trade winds. The composite wind vectors of the climatological mean, five highest and five lowest summer TWI years (Figure 3) illustrate that this proxy index may be of some use in determining trade wind strength. Figure 3(a) shows the climatological mean wind vector, Figure 3(b) illustrates the effects of highly positive TWI years, which is an enhanced trade wind pattern (wind speeds increased by ∼5–25%), greatest to the west of the Canary Islands above 25°N. Figure 3(c) illustrates the effects of highly negative TWI years, when between approximately 20 and 40°N the strength of the trade winds are reduced (note that the direction of the trade winds does not reverse, rather the strength of the north-easterly winds is being reduced, again by about ∼5–25%). Our TWI shows an increasing trend across all seasons from 1973 to 2012 (Figure 4(a)–(d)), suggesting trade wind strength, across the eastern boundary of the North Atlantic Ocean from 35 to 20°N, has significantly increased during the last 40 years [monthly and seasonally statistically significant, 1973–2012, with p values all <0.1 (Figure 4)]. We can extend our TWI back to 1871 using the nearest 20CR reanalysis grid box to Sal. Doing so indicates a previous rise from around 1910–1945, followed by a decline from 1945–1975 (Figure 4(f)). Further analysis regarding the historical accuracy of the reconstruction and mechanisms behind these changes goes beyond the scope of this paper; however, spectral analysis reveals an interesting ∼70-year cycle in the long-term record (Figure 4(f)). Impacts of the TWI on Macaronesian temperatures and precipitation are discussed in Sections 3.2., 3.3. and 4.

3.2. Temperature

Our four reference stations are Ponta Delgada (Azores), Santa Cruz De Tenerife Daily (Canary Islands), Sal (Cape Verde) and Funchal (Madeira). Ponta Delgada passes all three location specific tests for homogeneity. Funchal fails the SNHT and Buishand test at 1986 and 1976 respectively. With no sign of any abrupt shifts and no obvious outliers after visual observation and running variance analysis, we attribute this to gradual climate change – or potentially a function of the well-known climate ‘shift’ that occurred in 1976–1977 (Overland *et al.*, 2008) – as opposed to a physical inhomogeneity. The Santa Cruz and Sal record both fail the SNHT test at a similar time (1994 and 1995 respectively). We identify that the Santa Cruz record fails the homogeneity test because of a rapid (1.5–2 °C) temperature swing between 1994–1995 and 1996–1997. Martín *et al.* (2012) attribute an early 1990s cooling to the effects of atmospheric dimming from the Mt. Pinatubo eruption which, superimposed on the general 1990s warming trend, might explain the apparent sudden shift in temperatures. The shift is also apparent in temperature records from the other Canary Islands and the nearest ERA-I and NCEP/NCAR grid boxes (not shown), leading us to accept this as a natural variation rather than an inhomogeneity requiring adjustment. A similar pattern occurs for the Sal record from 1994 to 1997 (and also across the three other Cape Verde stations) so we again take no action to alter the record. This shift is also apparent in the Azores and Madeira records but is not as pronounced. Relative homogeneity corrections [all category 2 adjustments (Section 2.1.)] are applied to the following stations (Table 1): Ponta Delgada Daily (January 1973 to July 1988), Santa Maria (May 1964 to September 1981), Las Palmas (December 1889 to January 1983), Porto Santo (January 1940 to April 1949; June 2000 to July 2012)

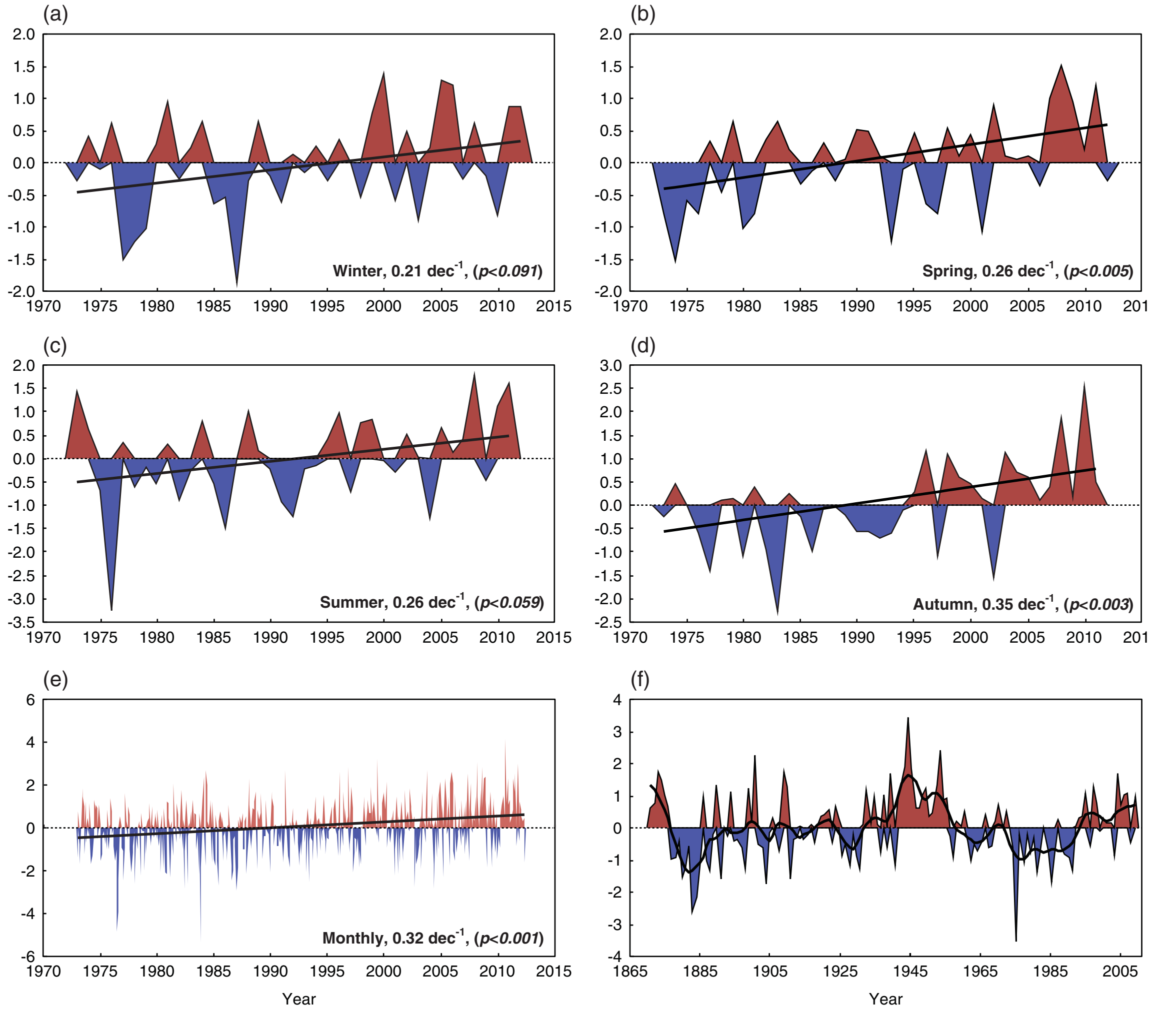

Figure 4. (a) The station-based seasonal (a–d) and monthly (e) Trade Wind index, 1973–2012 and (f) the extended summer (JJA) Trade Wind index, 1871–2010. The northern station is the SLP record from Ponta Delgada, and the southern station is the SLP record from Sal. The black lines (a–e) represent the 1973–2011/2012 Thiel-Sen trends and (f) an 11-year LOESS filter.

and Sal (January 1973 to December 1981). The regression splicing between stations results in a continuous, gap-free monthly temperature record from 1865 for the Azores and Madeira, 1884 for the Canary Islands and 1895 for Cape Verde (Figure 5). Descriptive statistics and trends for climatological 'normal' periods are given (Tables 2 and 3).

Annual interquartile range across the entire time period is 5.2 °C for the Azores, 3.4 °C for Cape Verde and 4.8 °C and 4.6 °C for the Canary Islands and Madeira respectively. Annual temperatures increase as latitude decreases. The modulating effect on the islands' temperature due to the ocean is evidenced by the similarity of standard deviations for all months across all locations (Table 2). Generally, the four Island temperature records display quite consistent variability (Figure 6). The exception is the early part of the Madeira record (1865–1915), where a cooling trend [strongest in winter (Table 3)] results in lower temperatures than for the other three islands. Warm peaks are centred around 1900, 1927 and 1939, with a synchronous cool trough in the early 1970s, which is followed by a rapid warming phase continuing until present. The trends for the entire time period (1865–2011) and the standard century (1901–2000) are characterized by warming throughout (with the exception of Azores winter, Table 3), although generally these trends are not significant and there is little sustained change before the late twentieth century temperature rise. The magnitude of the 1981–2010 temperature increase surpasses any previous temperature variability (the only exception to this is Madeiran winter temperature during 1911–1940). Recently, summer is the season with the most prominent temperature increase (Table 3) with trends in the range of 0.32–0.46 °C per decade rise. Accordingly, the first decade of the twenty-first century is the warmest decade on record for all the island chains. Meanwhile, 1971–1980 was the coldest decade for the Azores, 1951–1960 and 1971–1980 the joint coldest for the Canary Islands, 1941–1950 for Cape Verde and 1901–1910 for Madeira. Additionally, the twenty-first century contains seven of the warmest ten years on record for Madeira, and three out of ten for the other island

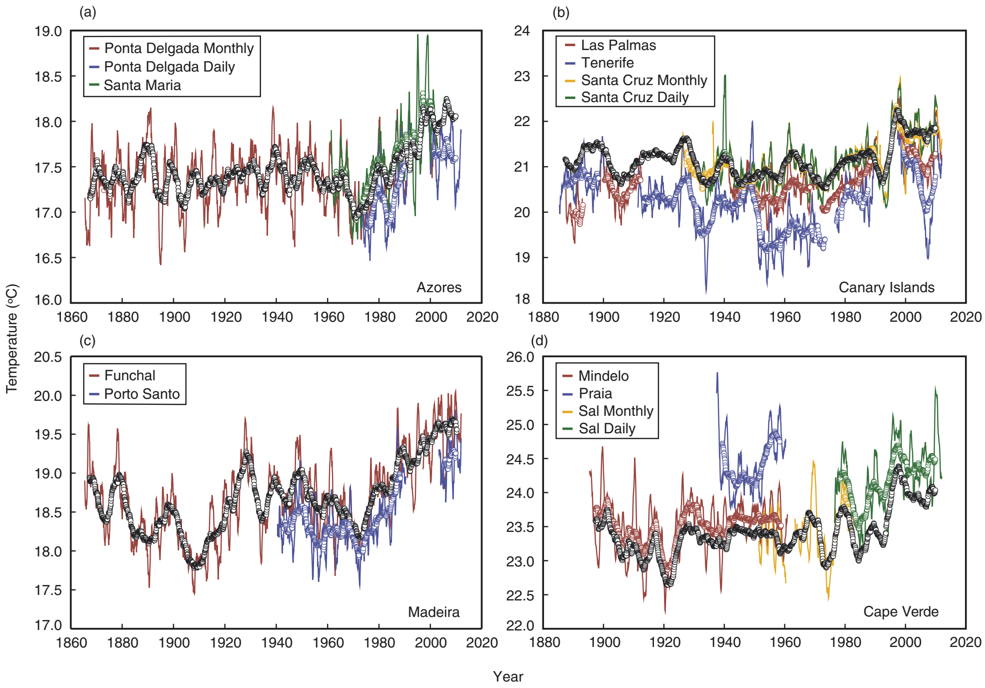

Figure 5. The reconstructed monthly time series of (a) the Azores, (b) the Canary Islands, (c) Madeira and (d) Cape Verde. The 12-month running means of each station used in the reconstruction (as lines) and the 60-month running means of the stations (as circles, black circles indicate the 60-month running mean of the final island time series) are displayed.

chains. Using the bias adjusted GHCN v3 global average as a base (0.91 °C per century, Lawrimore *et al.*, 2011), we report that annually, for 1901–2010, the Azores, Canary Islands and Cape Verde warmed at ratios of 0.57, 0.67 and 0.95 of the global average for this period, with Madeira exceeding the global average, warming at a rate of 1.37 times greater (a portion of this was due to the aforementioned early twentieth century lower temperatures). For 1981–2010, all four island chains exhibit warming rates greater than the global average of 0.27 °C per decade at a ratio of 1.21, 1.11, 1.22 and 1.40 times greater for the Azores, Canary Islands, Madeira and Cape Verde respectively. The prominence of the late twentieth century temperature rise is further highlighted by the fact that these island stations in the middle of the North Atlantic Ocean exhibit typically clearer signal-to-noise ratios due to the stability of the surrounding maritime environment.

Correlation coefficients between monthly temperature anomalies (1981–2010 base) and the monthly NAOI (across the longest possible temporal periods based on the islands temperature record) are 0.08, −0.27, −0.16 and −0.23 for the Azores, Canary Islands, Madeira and Cape Verde respectively [all significant ($p < 0.01$) given the long temporal period]. Seasonally, the relationships are stronger, particularly in winter (DJF), where the long-term correlations are (again for the Azores-Cape Verde) $r = 0.21$, −0.38, −0.19 and −0.44: all significant ($p < 0.01$). Removing the long-term linear trend from both records does not significantly change the relationship. The positive Azores correlation and negative correlation for the other islands are as expected and follow the well-documented SST-tripole pattern (Peng *et al.*, 2005). For the Macaronesian Island chain, it is simple to think of this increasing negative correlation with decreasing latitude as a result of the distance–decay relationship between the islands and the Azores high-pressure system. More simply, the Azores will usually be close to the centre of action of the semi-permanent high pressure system, so changes in its strength and location will not have as vast an effect on Azores temperature (but significant impacts in precipitation – Section 3.3.), whereas the islands further south will be more sensitive to changes in the high pressure. Theoretically, a stronger Azores high would result in stronger trade winds due to the enhanced subtropical-tropic pressure gradient, resulting in decreased temperatures due to the more intense trade winds bringing cool oceanic air and intensifying coastal upwelling. In contrast, a weaker Azores high would diminish the trade wind strength, allowing warm sea-surface temperature anomalies to develop; as was the case during the aforementioned exceptionally low NAOI of winter 2009/2010. A weaker Azores high also allows less dominant (i.e. non-NAO type structures) modes of variability to dominate. Correlation between the NAOI and the surface air temperature from the ERA-I reanalysis (Figure 7) illustrates this pattern. The basic pattern in winter and summer remains the same, but the relationship is stronger in winter (Figure 7(a)) than in summer (Figure 7(b)). The summer correlation patterns are weaker and shifted polewards, linked with the seasonal migration of the Azores High.

The winter temperature correlations with the TWI are very similar to the winter NAOI induced patterns,

Table 2. Macaronesian annual and monthly average temperatures (standard deviations in parentheses) for 1865–2011 (1885–2011 and 1895–2011 for the Canary Islands and Cape Verde respectively).

Location	Mean temperature (°C)												
	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Azores	17.4 (2.9)	14.5 (0.8)	14.1 (0.7)	14.4 (0.7)	15.2 (0.7)	16.6 (0.7)	18.9 (0.7)	21.0 (0.7)	22.1 (0.7)	21.1 (0.7)	19.1 (0.8)	16.9 (0.8)	15.4 (0.7)
Canary Islands	21.1 (2.7)	17.9 (0.7)	18.0 (0.9)	18.6 (0.9)	19.3 (0.8)	20.6 (0.8)	22.5 (0.8)	24.4 (0.9)	25.2 (1.0)	24.5 (0.8)	23.1 (0.8)	20.8 (0.8)	18.8 (0.8)
Cape Verde	23.4 (2.0)	21.3 (0.7)	20.9 (0.9)	21.3 (1.0)	21.7 (0.8)	22.4 (0.7)	23.4 (0.7)	24.4 (0.7)	25.7 (0.7)	26.4 (0.7)	25.9 (0.7)	24.5 (0.7)	22.5 (0.8)
Madeira	18.7 (2.6)	15.8 (0.8)	15.7 (0.8)	16.1 (0.9)	16.7 (0.8)	17.9 (0.7)	19.7 (0.7)	21.4 (0.7)	22.4 (0.8)	22.2 (0.7)	20.8 (0.7)	18.6 (0.8)	16.8 (0.8)

due largely in part to the overriding influence of the strength of the Azores high and its more fixed winter location (The NAOI and TWI very much represent a similar effect across Macaronesia in winter, but differ across summer). The summer NAOI and TWI indices display a negative correlation with ERA-I temperatures (Figures 7(b) and 8(b)) across the East-Atlantic from 35°N-25°N; a region for which we might have expected a negative correlation, given the mean climatological wind direction (Figure 3(a)). It would therefore seem that for 1981–2010, the summer trade winds have a potential effect on temperatures across Madeira and the Canary Islands (Figures 7(b) and 8(b)). Contrary to this (seen when comparing the TWI only, Figure 8(b)) is the area of positive temperature correlation stretching from NW Africa to the Atlantic south of 20°N. We attribute this correlation to the potential effect of the northeasterly trade winds (which are generally weaker across land) transporting warm continental air (whereas across the region of negative correlation, the prevailing winds travel over the ocean, so will be carrying much cooler air – explaining the observed pattern quite well (Figure 8(b)).

3.3. Precipitation

Mean annual and seasonal values are presented for 11 precipitation stations in addition to their seasonal 1981–2010 trends and correlation with the NAOI (Table 4). The only station to fail homogeneity tests was Ponta Delgada (pre-September 1939 values altered). For the Canary Islands, missing values at the selected GHCN stations are directly replaced with the station of the same name in the ECA dataset, as the monthly values were identical across the overlapping periods. The two stations for Madeira required minimal gap filling. The records for the three Azores stations all stop reporting in the early 2000s, and are extended using regression with either a nearby daily station (Ponta Delgada) or the nearest ERA-I grid box (Horta, Santa Maria). Because precipitation is reasonably distributed throughout the year, the regression relationships provide a reasonably accurate way to fill the gaps (the Azores records follow a more 'normal' distribution than the other islands). The reanalysis and nearby station values are very similar and the monthly correlations high ($\sim r = 0.9$). Unfortunately this is not the case for the three Cape Verde stations, two of which (St. Vincent and Praia) stop reporting in the 1970s. There are no suitable stations for comparison, and regression with the nearest reanalysis grid box (NCEP-NCAR as opposed to ERA-I due to the temporal coverage) is unsuitable here, as precipitation events are inconsistent, and typically confined to the wet (ASO) season. The nearest reanalysis grid box for the Cape Verde stations tends to overestimate the lower magnitude events and underestimate the significant precipitation events, unlike for the Azores where the magnitudes are very similar. This appears to be a general reanalysis issue, with the equivalent ERA-I grid boxes illustrating the same over/underestimations. We speculate this to be a function of the typical precipitation generation

Table 3. Macaronesian seasonal and annual temperature trends over selected and standard periods.

Location	ANN	DJF	MAM	JJA	SON
	Trend (°C/dec)				
1865–2011/2012					
Azores	**0.03**	0.03	0.03	0.01	0.05
Canary Islands (1885-)	0.02	0.03	0.03	0.04	0.01
Madeira	**0.06**	**0.09**	**0.06**	0.01	0.08
Cape Verde (1895-)	**0.07**	**0.06**	**0.06**	**0.08**	**0.05**
1865–1910					
Azores	0.01	0.11	0	−0.02	−0.03
Madeira	**−0.20**	**−0.24**	**−0.18**	**−0.18**	**−0.20**
1901–2000					
Azores	0.02	−0.02	0.03	0.02	0.06
Canary Islands	0.02	0.00	0.02	0.05	0.00
Madeira	**0.09**	**0.10**	0.08	0.04	**0.11**
Cape Verde	0.05	0.05	0.06	0.06	0.04
1911–1940					
Azores	0.10	0.06	0.21	0.06	0.05
Canary Islands	−0.15	−0.19	−0.05	−0.15	−0.14
Madeira	**0.31**	**0.33**	**0.41**	0.18	0.18
Cape Verde	0.17	0.15	0.18	0.20	0.18
1931–1960					
Azores	−0.04	−0.18	−0.08	0.04	0.06
Canary Islands	−0.05	−0.05	−0.11	0.07	0.04
Madeira	−0.03	0	−0.16	−0.13	0.15
Cape Verde	−0.02	0	−0.18	0.01	0.07
1981–2010					
Azores	**0.33**	0.27	0.28	0.32	0.23
Canary Islands	0.30	0.27	0.25	**0.40**	0.25
Madeira	**0.33**	0.24	**0.41**	**0.46**	0.16
Cape Verde	**0.38**	0.32	0.27	**0.41**	**0.38**

All trends are reported in degrees Celsius per decade (°C/dec). Bold indicates significant trends above 90% where the data passed both the standard and modified Mann–Kendall tests for significance.

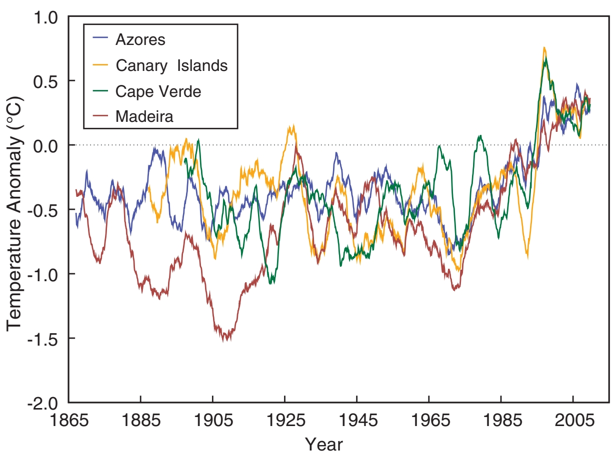

Figure 6. The temperature anomaly (1981–2010 base) for each of the four Macaronesian regions (60-month running mean).

mechanisms that operate across the different island chains (i.e. the Azores are more influenced by synoptic-scale depressions with Cape Verde influenced by inversion style events and the propagation of African Easterly waves and the seasonal Inter-Tropical Convergence Zone migration). Therefore, for St Vincent and Praia, we present the trends for the station from the 1880s to 1970s, and for the nearest NCEP/NCAR grid box from 1948 to present. The trends across the common time periods are in the same direction, but their magnitudes differ because of the aforementioned under/overestimation problem. Long-term temporal changes are depicted in Figure 9. Precipitation decreases with decreasing latitude. The Azores and Madeira have precipitation all year round, although the summer magnitudes are much smaller. The stations from 'flat' islands, such as Santa Maria, Porto Santo and Fuerteventura all have lower precipitation values than associated islands in their group that are more mountainous. Summer precipitation is rare for the Canary Islands and for Cape Verde from December to May. Significant negative correlations with the NAOI are displayed for the Azores across all seasons and Madeira for winter (Table 4). We also applied the correlations using a masked NAOI (just the negative/ positive NAOI years) but changes in the values were negligible. The coefficient of variation of annual monthly precipitation ranges from 16 to 24% for the Azores, 26 to 33% for Madeira, 40 to 52% for the Canary Islands and 77 to 108% for Cape Verde. This indicates the high degree of precipitation variability across Macaronesia, that again, changes as a function of latitude (for example, it would be 'normal' for one year in the Canary Islands to have 40–52% more or less rainfall than the year before, without this being a function of any secular change). Recent increases in Cape Verde wet season (ASO) precipitation are evident in all three

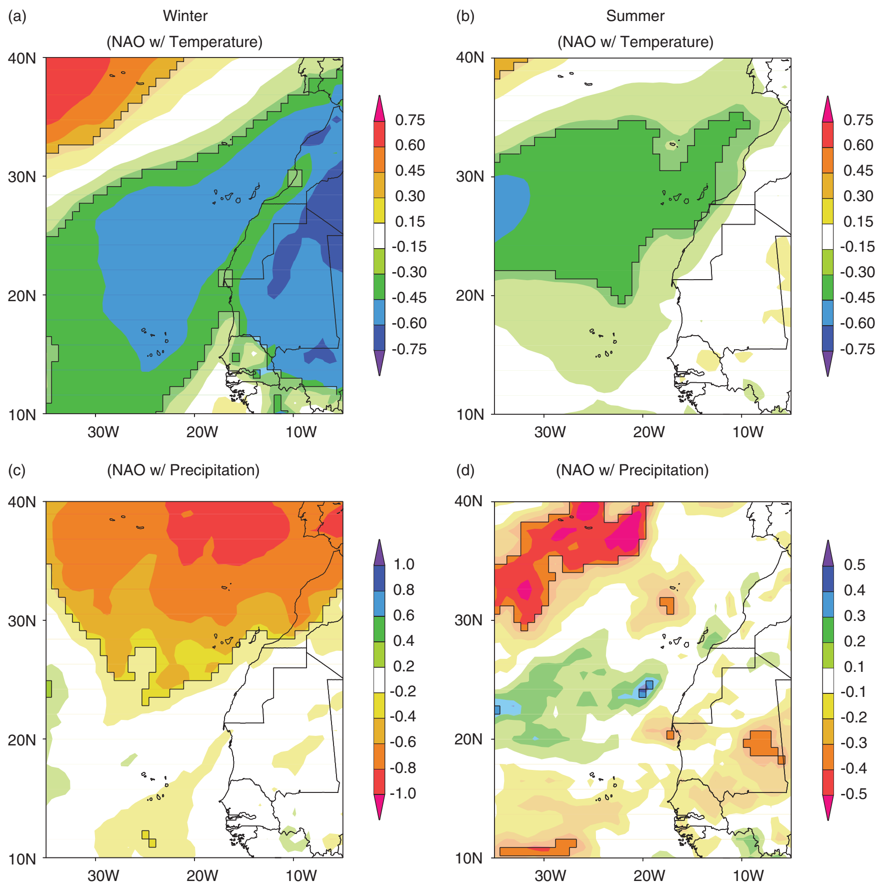

Figure 7. The correlation coefficient between the detrended anomalies of our extended Azores station-based NAOI with 2-m air temperature (a, b) and surface precipitation (c, d) from the ERA-Interim reanalysis across 1979–2011/2012 during winter (DJF) and summer (JJA). Black lines indicate areas statistically significant at 10%.

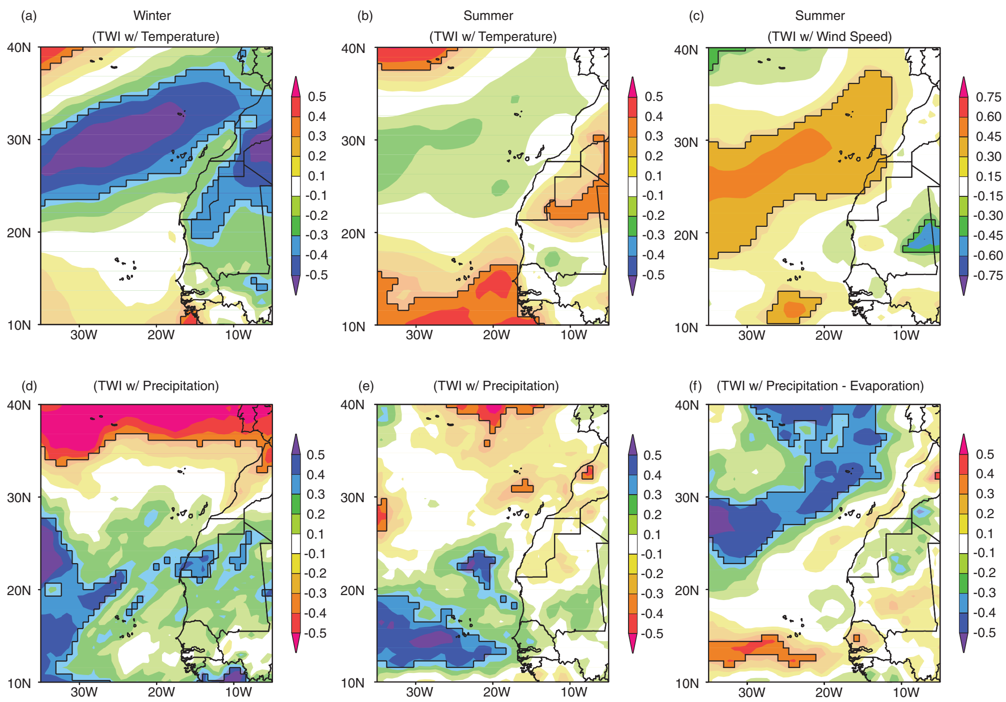

Figure 8. The correlation coefficient between the detrended anomalies of our station-based TWI with 2-m air temperature (a, b), wind speed anomalies (c), surface precipitation (d, e), and *P–E* (f) from the ERA-Interim reanalysis across 1979–2011/2012 during winter (only for temperature and precipitation) and summer. Black lines indicate areas statistically significant at 10%.

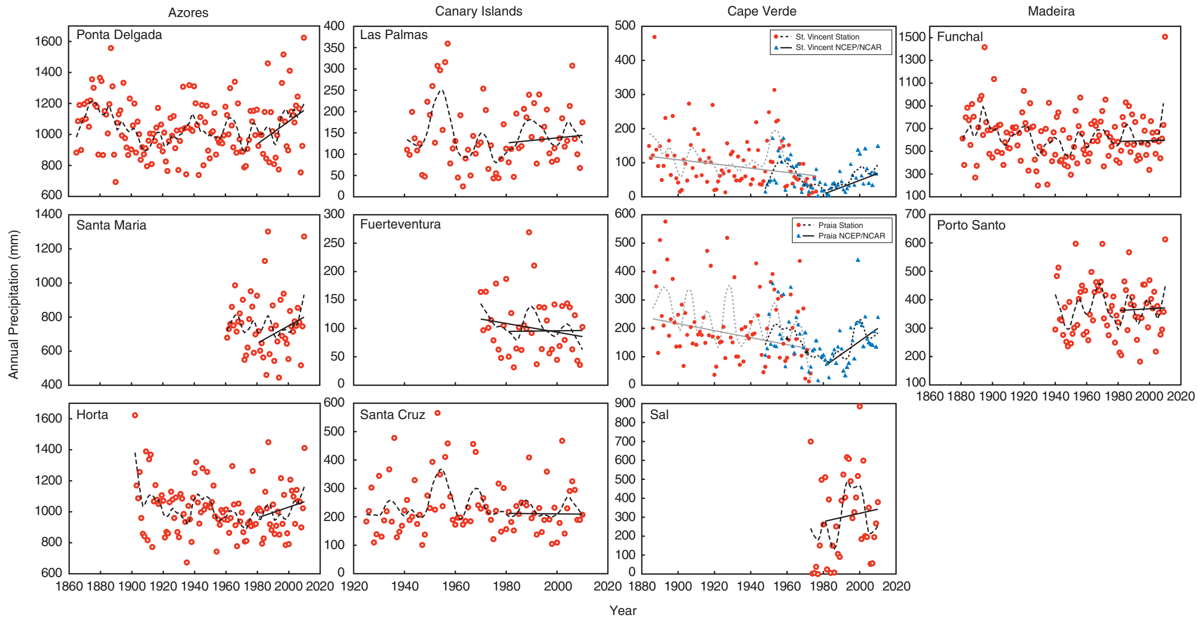

Figure 9. Annual precipitation (mm) records from various Macaronesian sites with their 1981–2010 Thiel-Sen trend line and long-term 11-year LOESS filters.

records from the 1980s onwards [statistically significant for St. Vincent and Praia (Table 4)] although this trend appears to have reversed at Sal during the last 10 years (Figure 9). All three stations are situated at sea level (Table 1), although they have contrasting locations on their respective islands, and the orography of each island also differs markedly. Santiago (the island where the station at Praia is located) has the highest peak, with St. Vincent and Sal significantly lower (1394, 725 and 406 m respectively). However, all three sites (the Sal Station and nearest grid boxes for St. Vincent and Praia) show similar increasing precipitation trends in the late twentieth century. This increase corresponds with the recent recovery of Sahel precipitation (Hoerling *et al.*, 2010). General consensus on the drivers of inter-annual Sahel precipitation variability have yet to be reached, although changes in tropical SSTs across the Atlantic, Pacific and Indian Oceans (Lu and Delworth, 2005) in addition to changes in North Atlantic oceanic heat transport (Baines and Folland, 2007) have been shown to display potential relationships. Factors influencing Cape Verde precipitation are: (1) seasonal migration of the Azores high and equatorial low and the resultant effect on trade wind and Canary Current strength (Mannaerts and Gabriels, 2000) and (2) the west-African monsoon, which brings south-westerlies, easterly waves and isolated convection events. Given the lack of significant rainfall increase elsewhere across the Macaronesian archipelago, it would seem that changes in the West African monsoon may represent a significant factor in recent changes, potentially owing to an increased maritime-continental temperature gradient associated with general global warming. Bielli *et al.* 2010 indicate that both the African Easterly Jet and the West African Monsoon Index (WAM) have been increasing since the early 1980s, although the WAM has not yet fully recovered since its abrupt decease around 1967 (Li and Zeng, 2002). Therefore it is likely that Cape Verde precipitation and the WAM are related.

The spatial NAOI with ERA-I rainfall correlation pattern in winter displays a very strong negative correlation across the Azores, Madeira and the western and central Canary Islands (Figure 7(c)). A weaker NAOI will result in more southerly-displaced storm tracks, and therefore more precipitation, explaining the observed pattern quite well. Correlations between the individual Canary Island stations (Table 4) and precipitation do not support this, but this can be explained by lack of the eastern islands' correlation with the NAO (García-Herrera *et al.*, 2001) and the location of the stations at Santa Cruz and Las Palmas in the rain shadow regions (eastern sides) of their respective islands. The summer pattern (Figure 7(d)) shows a much weaker, northwestward shifted connection than in winter, due to the aforementioned weaker and more northeasterly-displaced Azores High. As seen with temperature, the TWI-precipitation correlation pattern shows a similar winter structure to the NAOI-precipitation pattern (Figure 8(d)). Summer NAOI-precipitation correlations across the three northernmost island chains merit little attention, due to the general lack of or small precipitation amounts during this season. Walsh and Portis (1999) highlighted the mean negative state of precipitation minus evaporation ($P - E$) across the eastern North Atlantic (35–20°N) and here we find our TWI relationship with $P - E$ is strongly negative, indicating that enhanced trade winds serve to increase evaporation across northwest Macaronesia (Figure 8(f)). Interestingly, where the area of significant TWI correlation with P–E ends, below this (southwest of the Canary Islands and along 20–10°N) is

Table 4. Macaronesia station precipitation long-term annual and seasonal means (standard deviations in parenthesis), linear trends for the 1981–2010 period and correlation coefficients with the North Atlantic Oscillation Index for the entire record.

Island Chain	Station	Temporal coverage	Mean (standard deviation) (mm)					1981–2010 Trend (mm/dec)				NAO correlation			
			Annual	DJF	MAM	JJA	SON[a]	DJF	MAM	JJA	SON[a]	DJF	MAM	JJA	SON[a]
Azores	Ponta Delgada	1865–2012	1044.2 (178.6)	343.5 (115.8)	252.6 (84.6)	135.1 (53.2)	313.6 (88.6)	29.1	24.7	14.3	−15.7	***−0.64***	***−0.60***	***−0.31***	***−0.40***
Azores	Santa Maria	1961–2012	753.6 (178.2)	273.5 (115.7)	164.9 (71.2)	81.3 (43.8)	233.7 (82.6)	14.4	7.6	7.7	−16.2	***−0.78***	***−0.70***	−0.25	***−0.40***
Azores	Horta	1902–2012	1017.5 (166.9)	328.1 (103.0)	236.5 (76.0)	143.8 (59.4)	307.6 (82.0)	22.8	17.0	1.6	−17.4	***−0.56***	***−0.58***	***−0.38***	***−0.43***
Canary Islands	Las Palamas	1941–2012	143.3 (74.8)	75.9 (58.5)	20.6 (19.1)	1.5 (3.3)	46.1 (41.5)	15.1	−4.1	0	1.9	0.03	0.15	**0.26**	0.11
Canary Islands	Fuerteventura	1970–2012	103.6 (52.4)	61.0 (39.3)	18.6 (18.9)	0.3 (0.7)	24.6 (20.9)	−3.5	−1.0	0	1.6	0.02	0.10	−0.11	−0.27
Canary Islands	Santa Cruz M	1925–2012	237.0 (95.8)	120.0 (71.5)	49.9 (42.9)	1.8 (5.0)	66.1 (49.3)	12.6	2.9	0	−5.0	−0.14	***0.28***	0.05	−0.06
Cape Verde	St. Vincent	1883–1976	76.0 (80.6)	9.3 (11.3)	1.6 (4.2)	27.9 (33.0)	85.5 (69.5)	–	–	–	–	0.07	0.04	−0.08	0.10
Cape Verde	St. Vincent NCEP/NCAR Grid	1948–2012	58.5 (43.1)	2.0 (3.7)	0.6 (1.7)	16.9 (16.6)	52.9 (39.0)	0	0	4.2	**15.2**	***−0.36***	0.03	−0.11	−0.05
Cape Verde	Praia	1885-1973	160.5 (173.5)	5.8 (10.0)	0.3 (1.5)	78.4 (91.8)	201.2 (160.4)	–	–	–	–	0.18	0.11	**−0.24**	−0.01
Cape Verde	Praia NCEP/NCAR Grid	1948–2012	152.0 (83.4)	1.5 (4.2)	0.1 (0.5)	59.2 (40.4)	138.4 (73.7)	0	0	11.9	**38.7**	−0.22	−0.08	−0.06	0.08
Cape Verde	Sal	1973–2012	293.0 (228.3)	97.9 (149.7)	36.0 (115.4)	47.3 (89.9)	126.8 (144.1)	0	0	2.1	17.5	0.12	0.07	−0.04	−0.17
Madeira	Funchal	1880–2012	629.3 (210.7)	261.7 (144.1)	136.1 (77.8)	15.1 (23.9)	215.0 (130.8)	6.1	−2.6	−1.3	−0.7	***−0.58***	***−0.32***	−0.13	***−0.43***
Madeira	Porto Santo	1940–2012	367.2 (95.4)	153.1 (77.5)	78.4 (40.1)	15.5 (9.6)	118.2 (58.5)	11.2	−3.0	1.1	4.1	***−0.63***	−0.01	−0.05	−0.22

All trends are reported in millimetres per decade (mm/dec). Bold indicates significant trends above 90% where the data passed both the standard and modified Mann-Kendall tests for significance. For the correlation values, bold indicates 95% and emboldened italics indicates 99% significance. [a]For Cape Verde only, the three month autumn period is ASO rather than SON, to better capture the wet season.

an area of significant positive correlation of TWI with precipitation (Figure 8(e)).

4. Macaronesian climate change in context

The 1981–2010 temperature increase is unprecedented in our Macaronesian record. Comparisons with previously reported trends (Section 1) indicate that the Azores, Canary Islands and Cape Verde (0.33, 0.30 and 0.38 °C per decade rise respectively) annual warming exceeds previously published values (mainly due to our more up-to-date records, which include more recent warm years), although the magnitude of warming at Madeira (0.33 °C per decade rise) appears to be less. This is likely because of a combination of previous authors' use of standard least-squares linear regression (with an algorithm designed to find the maximum trends) as opposed to the Thiel-Sen regression used here (as the former is more susceptible to outliers and will often overestimate trends) and different time periods considered. The small range between our values across the four island chains and the similar pattern of seasonal trends between the island groups gives us confidence in the warming magnitudes. In terms of precipitation, trends in the Cape Verde wet season (ASO) are the only statistically significant increases, which fall in line with the recent recovery in African Sahel precipitation. Positive trends can be seen towards the end of the records for the Azores stations (Table 4, Figure 9) although these are not significant and similar rise and falls are evident in the longer-term records (i.e. Horta and Ponta Delgada). There are no apparent precipitation trends in the central, more mountainous Canary Island stations (Santa Cruz and Las Palmas), whereas on the eastern, flatter island at Fuerteventura, precipitation appears to be decreasing. Coincidentally, whilst not analysed here, the meteorological station from the ECA database at Izana, Tenerife, (2371 m altitude) experienced its driest hydrometeorological year (September to August) and winter (DJF) season during 2011–2012 (http://www.izana.org/). Our NAOI closely follows the Hurrell (1995) index [slightly different values due to a different base period (1865–2012 used here)]. Our TWI, based on the normalized SLP difference between the Azores and Cape Verde indicates a significant positive trend since the start of the station based record in 1973, suggesting stronger trade winds across the Macaronesian region of the North Atlantic. The NAOI strongly correlates with precipitation throughout the Azores across all seasons and with Madeira in winter (also during spring and autumn, but only for the more mountainous main island station at Funchal, Table 4). The significant zone of winter negative correlation (Figure 7(c)) extends southwards to the Canary Islands, but is not shown in the station-based records. The summer NAOI-precipitation correlation displays a similar but weaker pattern owing to the north-easterly migration of the Azores High. Correlations between the NAOI and temperature (Figure 7) display a strong meridional gradient, with a similar seasonal reduction in strength and spatial extent during summer.

Spectral and wavelet analysis of the detrended winter NAOI and TWI (not shown here) yields very similar results. For winter, significant peaks at 7.7, 21 and 73 years are found in our extended NAOI series, with 6 to 8- and 20-year peaks in the TWI. For summer, a 6.6-year NAOI peak and a 5.5-year TWI peak were identified. The similarity of spectral peaks for both indices, which have the semi-permanent Azores High as a centre of action, emphasize the importance of inter-annual variations in the Hadley cell (e.g. Wang, 2002) as a key factor in natural North Atlantic climate variability.

The links between Macaronesian climate and the NAOI may not always have been as described here. A simple running correlation between the NAOI and Macaronesian monthly temperature anomalies (Figure 10(a)) illustrates the non-stationary behaviour of the relationship. The annual values illustrate an interesting, potentially cyclic relationship. Polyakova *et al.* (2006) illustrated the relationship between the surface air temperature of the entire North Atlantic basin and the NAOI throughout time and found an interesting reversal in their relation (i.e. a negative correlation from 1910 to 1936 and a positive correlation from 1936 to 1963). Here, we identify a similar pattern. An increasing trend in annual NAOI-temperature correlation can be seen from 1910 to 1940, which remains positive until 1965 before declining for the rest of the century and seemingly starting to rise again since 2000 (these correlations curiously follow the general twentieth century warming and cooling trend, so we detrended the temperature and NAOI time series; yet the same patterns remained). Subsequently, comparisons of the winter NAOI-Azores temperature correlation and the Azores winter temperature time series appear distinctly in opposite phase from 1873–1981 (Figure 10(b)) before displaying synchronous behaviour since 1981. An explanation for this observation goes beyond the scope of this paper; however, changes are at least in some part due to a shift in the action centres of the NAOI (analogous to the seasonal migration to a more north-easterly position but acting on inter-annual timescales). Generally, more positive NAOI

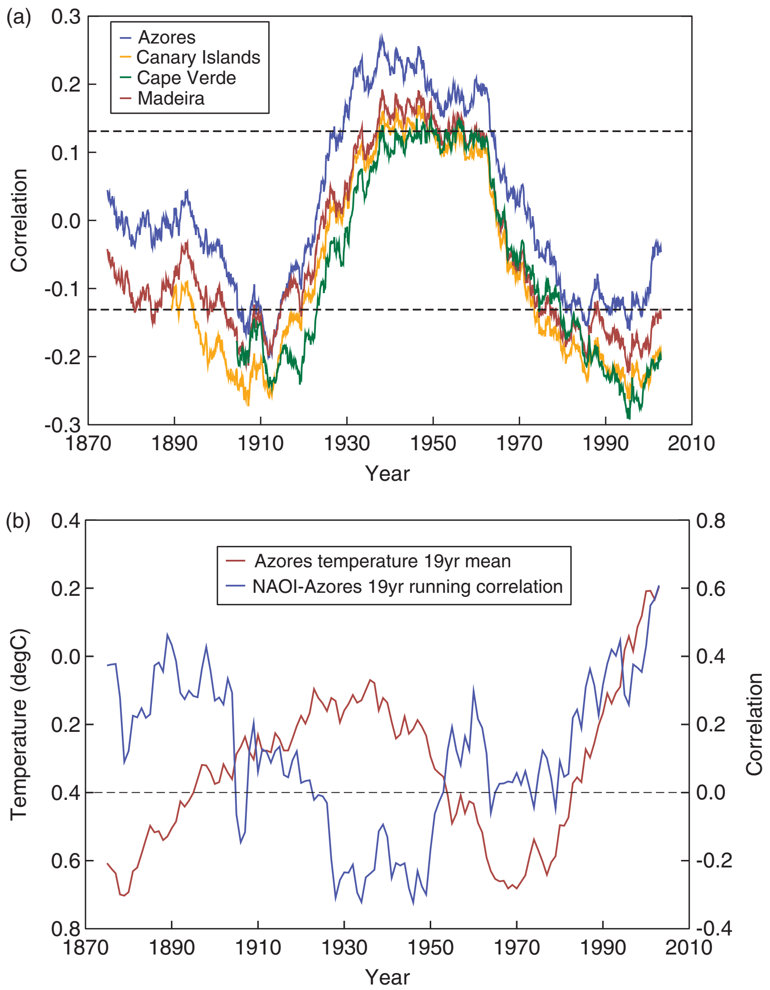

Figure 10. (a) The running correlation (19-year sliding window) between detrended monthly Macaronesian temperature anomalies and the monthly NAOI (dashed lines indicate the boundaries of 95% statistical significance for the correlations) and (b) the running correlation (19-year sliding window) between the detrended Azores winter temperature anomalies and detrended winter NAOI in addition to the 19-year running mean of the Azores winter temperature anomalies.

Table 5. Seasonal and annual temperature trends (1981–2010) for the GISS Global and European average and 14 mid-latitude island/atoll stations from the GHCN database.

Station	Country/region	Latitude	Longitude	Altitude (m)	ANN	DJF	MAM	JJA	SON
GISS	Global	90°S-90°N	0-360°E		**0.14**	**0.12**	**0.15**	**0.14**	**0.17**
GISS	Europe	35–65°N	10°W-30°E		**0.32**	0.25	**0.34**	**0.47**	0.19
Nassau	Bahamas	25°05′N	77°47′W	7	**0.40**	0.39	0.42	**0.47**	**0.35**
Minamitorishima	Japan	24°29′N	153°97′E	9	−0.04	0.13	−0.08	−0.12	−0.07
Honolulu	Hawaii	21°35′N	157°93′W	5	−0.07	0.05	0.11	−0.04	−0.26
Wake Island	USA	19°28′N	166°65′E	4	**−0.37**	−0.49	−0.35	−0.23	**−0.36**
San Juan	Puerto Rico	18°43′N	66°00′W	19	−0.05	−0.08	−0.06	0.02	−0.04
Kingston	Jamaica	17°93′N	76°46′W	14	0.21	0.13	0.10	0.11	0.18
Hato	Curaçao	12°19′N	68°97′W	67	0.10	0.04	0.10	0.15	0.08
Cocos (Keeling) Island	Australia	12°18′S	96°82′E	3	0.03	0.10	0.03	0.09	−0.06
St. Helena	British Overseas Territory	16°00′S	05°70′W	627	0.02	0.13	0.08	0.00	−0.12
St. Brandon	Mauritius	16°80′S	59°55′E	4	**0.31**	**0.33**	**0.35**	**0.30**	**0.31**
Rodrigues	Mauritius	19°68′S	63°42′E	59	**0.19**	0.24	0.21	0.12	0.17
Plaisance	Mauritius	20°43′S	57°67′E	57	**0.35**	**0.35**	**0.36**	**0.31**	**0.33**
Easter Island	Chile	27°15′S	109°42′W	51	0.09	0.11	0.08	0.18	0.14
Robinson Crusoe Island	Chile	33°67′S	78°97′W	30	−0.15	−0.22	−0.16	−0.17	−0.05

All trends are reported in degrees Celsius per decade (°C/dec). Bold indicates significant trends above 90% where the data passed both the standard and modified Mann-Kendall tests for significance.

values equate to an easterly shift in NAO position (Beranová and Huth, 2007) and a series of more negative years characterizes the (winter) NAOI from 1935 to 1970 with more positive values in the 1980s and 1990s (Figure 2). Ultimately, a temporally variable NAOI-Macaronesia relationship could result in spatially different correlation patterns to those shown in Figure 7 and described in Section 3 (especially given that the temporal period considered in Figure 7 (1981–2010) is during the period after the winter shift occurs in Figure 10(b)).

Whilst geographically unique, it is of interest to compare the Macaronesian islands to broadly similar sites (i.e. volcanic islands and atolls of similar latitude) and the recent general regional and global temperature trends. Therefore, Table 5 illustrates the 1981–2010 annual and seasonal decadal trends for selected island stations (all from the GHCN, treated for homogeneity and quality as in Section 2; no gap-filling methods are applied to these stations, and only stations between the latitudes of 10°–40° with >85% data during 1981–2010 were considered). Also shown are the area-averaged global and European trends from the Goddard Institute for Space Sciences (GISS) dataset (these are based on GHCN v3 data (Hansen *et al.*, 2010)). Firstly we notice a discrepancy of 0.15 °C per decade between the GISS (0.14 °C per decade, Table 5) and GHCN v3 (0.29 °C per decade) global averages. This is due to the GISS analysis incorporating the HadISST1 dataset (Rayner *et al.*, 2003), which therefore provides a much more comprehensive global coverage (including oceans) as opposed to the GHCN, which considers only land-based stations (Lawrimore *et al.*, 2011). Regardless of the global dataset considered, Macaronesian stations display higher–magnitude warming across all seasons (Table 3). When compared to the European trends from the GISS record (Table 5), Macaronesian stations show largely comparable trends across all seasons [a common trait amongst the GISS Europe and the Macaronesian stations appears to be enhanced trends during the heating portions (i.e. spring and summer) of the year], the only exception being Cape Verde during SON, which is double (0.38 °C per decade) the European average (September to November are still some of the warmest months of the year at the lower latitudes compared to what is autumn for Europe). Table 5 illustrates that out of the selection of fourteen mid-latitude island/atoll stations, nine of these display no significant or negative temperature trends, with the Macaronesian records ubiquitously displaying greater warming magnitudes for 1981–2010 (Table 3). Three stations from Mauritius all display positive warming trends, two of which (Plaisance and St. Brandon, Table 5) display seasonally significant warming trends (0.30–0.36 °C per decade) comparable to the trends displayed in the Macaronesia records (Table 3). Conversely, the station at Nassau, Bahamas, displays a much stronger annual trend (0.40 °C per decade) than the Macaronesian records but comparable seasonal trends. A full comparison of global island temperature records would make an ideal comparison to place recent Macaronesian warming in context; however, lacking this, from the limited observations shown here it would generally appear that the warming across Macaronesia is quite strong for island locations (although the trends from the stations across Mauritius suggest it is potentially a comparable analogue). However, we stress that direct comparisons are potentially hazardous because of the variable influences of island size, station location and regional climate variability.

5. Conclusions

Through the use of rigorous homogeneity tests and the fortuitous overlap of gaps in the historical record, we were able to reconstruct and present long-term temperature records for the four Macaronesia island chains. The magnitude of the 1981–2010 annual temperature increase is reasonably similar throughout (0.30–0.38 °C per decade) and exceeds the global average across all the island chains. The strongest increase is during summer, where significant trends for the Canary Islands, Madeira and Cape Verde were all at least 0.40 °C per decade. Such trends are concerning, and if they continue, will likely lead to environmental (e.g. exacerbation of heat waves and wildfires) and social problems for the islands. A direct relationship is evident between the islands' heights and precipitation recorded (more mountainous islands receive more precipitation, particularly on their windward sides), although the exact location of the meteorological stations on the islands is also clearly an important factor. Precipitation has shown recent (1981–2010) signs of increase across the Azores islands (not significant), insignificant change across Madeira and the Canary Islands and a significant increase in the Cape Verde wet season. We have presented: (1) an updated, purely station-based Azores-Iceland NAOI (previously, the Azores station record was replaced by reanalysis data since 2003) and (2) the TWI; a novel way to characterize trade-wind strength across the Macaronesian region of the North Atlantic, which eliminates problems associated with sampling wind speeds. The current relationships between Macaronesian precipitation, temperature and the NAOI have been discussed. Winter temperature correlations with the NAOI highlight a positive correlation across the Azores and a negative correlation with the other three islands. Additionally, the winter NAOI correlates negatively with precipitation across the Azores, Madeira and western and central Canary Islands. The summer patterns are similar, but weaker in extent and strength and are 'north-shifted', associated with the seasonal migration of the centre of the Azores high. This relationship is not stationary, and varies over longer timespans, as we have shown that the 19-year running correlation between the islands temperature and the NAOI changes sign every 30–40 years. The TWI is very similar to the NAOI during winter in terms of its effects on Macaronesian surface temperature and precipitation, due to the overriding influence of a then (seasonally) stronger Azores High. The difference between them is greater across summer, with the TWI displaying a negative correlation with temperatures across Madeira and the Canary Islands and a positive correlation with Cape Verde and northwest African temperatures. Additionally, the TWI displays a strong significant correlation with wind speed anomalies across a large part of Macaronesia, demonstrating its practicality, and also, correlates strongly with precipitation around Cape Verde (reflected in the significant increase in both the TWI and station-based precipitation records). The negative correlation of the TWI with $P - E$ represents a shift to more humid conditions across the northwestern Macaronesian region (including the Azores and Madeira), which can have a variety of negative impacts (e.g. human health and soil moisture deficit). The NAOI station-based indices will be continually updated, as a consistent methodology is important when studying long-term variability in atmospheric circulation over the whole North Atlantic, particularly as the NAO has become noticeably more negative (especially in summer) over the last decade. The temperature time series and the NAOI daily (not explicitly analysed here but still available, from 1944 to present), monthly (1865 to present) and TWI indices (extended 1871 to present and station-based 1973 to present) are freely available online (at www.pangea.de or by e-mail from the lead author).

We expect the TWI to be useful in future studies concerning the impacts of the trade winds on coastal upwelling across northwest Africa. Future studies concerning Macaronesian climate should focus on its time-varying relationship with the NAOI and TWI. Additionally the potential impacts of climate change with altitude and aspect (i.e. the windward and leeward sides of the islands) should be considered, as should the occurrence of extreme events (particularly sustained maximum temperatures, drought and fire events) given the relative lack of previous reports on Macaronesian climate in the English-language science literature. We have also demonstrated that long-term climate records can be reconstructed from fractured temporal records, even in the absence of long-term reference series. Efforts should be made to continue such actions at previously understudied locations.

Acknowledgements

The authors would like to thank Grant Bigg and two anonymous reviewers for providing a review and greatly improving the manuscript, and Paul Coles for assistance with the figures. This research was in part funded by a NERC doctorial training grant NE/I528618/1 and also from the University of Sheffield's Department of Geography.

References

Aguilar E, Auer I, Brunet M, Peterson TC, Wieringa J. 2003. WCDMP 53, *WMD/TD No. 1186: Guidelines on Climate Metadata and Homogenization*. World Meteorological Organization, Geneva, Switzerland.

Alexanderson H. 1986. A homogeneity test applied to precipitation data. *Journal of Climatology* **6**: 661–675.

Baines PG, Folland CK. 2007. Evidence for a rapid global climate shift across the late 1960s. *Journal of Climate* **20**: 2721–2744. DOI: 10.1175/JCL14177.1

Bakun A, Field DB, Redondo-Rodriguez A, Weeks SJ. 2010. Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. *Global Change Biology* **16**: 1213–1228. DOI: 10.1111/j.1365- 2486.2009.02094.x

Ball S. 2011. Exceptional rainfall in Gibraltar during winter 2009/10. *Weather* **66**(1): 22–25. DOI: 10.1002/wea.733

Beranová R, Huth R. 2007. Time variations of the relationships between the North Atlantic Oscillation and European winter temperature and precipitation. *Studia Geophysica et Geodaetica* **51**(4): 575–590. DOI: 10.1007/s11200-007-0034-3

Bielli S, Douville H, Pohl B. 2010. Understanding the West African monsoon variability and its remote effects: an illustration of the grid point nudging methodology. *Climate Dynamics* **35**: 159–174. DOI: 10.1007/s00382-009-0667-8

Bladé I, Liebmann B, Fortuny D, van Oldenborgh G. 2012. Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the Mediterranean region. *Climate Dynamics* **39**: 709–727. DOI: 10.1007/s00382-011-1195-x

Box J. 2002. Survey of Greenland instrumental temperature records: 1873–2001. *International Journal of Climatology* **22**: 1829–1847. DOI: 10.1002/joc.852

Buishand TA. 1982. Some methods for testing the homogeneity of rainfall records. *Journal of Hydrology* **58**: 11–27.

Cao LJ, Yan ZW. 2012. Progress in research on homogenisation of climate data. *Advances in Climate Change Research* **3**(2): 59–67. DOI: 10.3724/SP.J.1248.2012.00059

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen JA, Rinke A, Sarr A, Whetton P. 2007. Regional climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, United Kingdom and New York.

Climate Atlas. 2012. *Climate atlas of the archipelagos of the Canary Islands, Madeira and the Azores*. The Meteorological State Agency of Spain and the Institute of Meteorology, Portugal. http://www.meteo.pt/export/sites/default/bin/docs/tecnicos/Atlas__Climatico_ilhas.pdf

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk M, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ. 2011. The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society* **137**: 1–28. DOI: 10.1002/qj.776

Costa A, Soares A. 2009. Homogenization of climate data: review and new perspectives using geostatistics. *Mathematical Geosciences* **41**(3): 291–305. DOI: 10.1007/s11004-008-9203-3

Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Hólm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette J-J, Park B-K, Peubey C, de Rosnay P, Tavolato C, Thépaut JN, Vitart F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**: 553–597. DOI: 10.1002/qj.828

Drápela K, Drápelová I. 2011. Application of Mann-Kendall test and the Sen's slope estimates for trend detection in deposition data from Bílý Kríž (Beskydy Mts., the Czech Republic) 1997–2010. *Beskydy* **4**(2): 133–146 ISSN: 1803–2451.

García-Herrera R, Gallego D, Hernandez E, Gimeno L, Ribera P. 2001. Influence of the North Atlantic oscillation on the Canary Islands precipitation. *Journal of Climate* **14**: 3889–3903. DOI: 10.1175/15200442(2001)014 < 3889:IOTNAO > 2.0.CO;2

García-Herrera R, Gallego D, Hernandez E, Gimeno L, Ribera P. 2003. Precipitation trends in the Canary Islands. *International Journal of Climatology* **23**: 235–241. DOI: 10.1002/joc.870

Granato GE. 2006. *Kendall-Theil Robust Line (KTRLine-–version 1.0)-A Visual Basic Program for Calculating and Graphing Robust Nonparametric Estimates of Linear-Regression Coefficients between Two Continuous Variables*. Techniques and Methods of the U.S. Geological Survey, 4(7): U.S. Geological Survey.

Hagen E. 2001. Northwest African upwelling Scenario. *Oceanologica Acta* **24**(S): 113–128. DOI: 10.1016/S0399-1784(00)01110-5

Hamed KH, Rao AR. 1998. A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology* **204**: 182–196.

Hanna E, Jónsson T, Box JE. 2004. An analysis of Icelandic Climate since the nineteenth century. *International Journal of Climatology* **24**: 1193–1210. DOI: 10.1002/joc.1051

Hanna E, Jónsson T, Ólafsson J, Valdimarsson H. 2006. Icelandic coastal sea-surface temperature records constructed: putting the pulse on air-sea-climate interactions in the northern North Atlantic. Part 1: comparison with HadISST1 open ocean surface temperatures and preliminary analysis of long-term patterns and anomalies of SSTs around Iceland. *Journal of Climate* **19**(21): 5652–5666. DOI: 10.1175/JCLI3933.1

Hanna E, Cappelen J, Allan R, Jónsson T, Le Blancq F, Lillington T, Hickey K. 2008. New insights into North European and North Atlantic surface pressure variability, storminess, and related climatic change since 1830. *Journal of Climate* **21**: 6739–6766. DOI: 10.1175/2008JCLI2296.1

Hansen JR, Ruedy R, Sato M, Lo K. 2010. Global surface temperature change. *Reviews of Geophysics* **48**: RG4004. DOI: 10.1029/2010RG000345

Harris MF, Finger FG, Teweles S. 1961. Diurnal variation of wind, pressure, and temperature in the troposphere and stratosphere over the Azores. *Journal of the Atmospheric Sciences* **19**(2): 136–149.

Hoerling MP, Eischeid J, Perlwitz J. 2010. Regional precipitation trends: distinguishing natural variability from anthropogenic forcing. *Journal of Climate* **23**(8): 2131–2145. DOI: 10.1175/2009JCLI3420.1

Hu ZZ, Wu Z. 2004. The intensification and shift of the annual North Atlantic Oscillation in a global warming scenario situation. *Tellus A* **56**: 112–124. DOI: 10.1111/j.1600-0870.2004.00050.x

Hurrell JW. 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. *Science* **269**: 676–679. DOI: 10.1126/science. 269.5224.676

Hurrell JW, Deser C. 2009. North Atlantic climate variability: the role of the North Atlantic Oscillation. *Journal of Marine Systems* **79**: 231–244. DOI: 10.1016/j.jmarsys.2008.11.026

Jain SK, Kumar V. 2012. Trend analysis of rainfall and temperature data for India. *Current Science India* **102**(1): 37–49.

Jones P, Davies T, Lister D, Slonosky V, Jónsson T, Bärring L, Jönsson P, Maheras P, Kolyva-Machera F, Barriendos M, Martin-Vide J, Rodriguez R, Alcoforado M, Wanner H, Pfister C, Luterbacher J, Rickli R, Schuepbach E, Kaas E, Schmith T, Jacobeit J, Beck C. 1999. Monthly mean pressure reconstructions for Europe for the 1780–1995 period. *International Journal of Climatology* **19**: 347–264. DOI: 10.1002/(SICI)10970088 (19990330)19:4 < 347::AID-JOC363 > 3.0.CO;2-S

Jónsson T, Gardarsson H. 2001. Early instrumental meteorological observations in Iceland. *Climatic Change* **48**: 169–187. DOI: 10.1023/A:1005617512142

Jónsson T, Hanna E. 2007. A new day-to-day pressure variability index as a proxy of Icelandic storminess and complement to the North Atlantic Oscillation index 1823–2005. *Meteorologische Zeitschrift* **16**(1): 25–36. DOI: 10.1127/0941- 2948/2007/0177

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletins of the American Meteorological Society* **77**: 437–471. DOI: 10.1175/15200477 (1996)077 < 0437:TNYRP > 2.0.CO;2

Klein Tank AMG, Wijngaard JB, Können GP, Böhm R, Demarée G, Gocheva A, Mileta M, Pashiardis S, Hejkrlik L, Kern-Hansen C, Heino R, Bessemoulin P, Műller-Westermeier G, Tzanakou M, Szalai S, Pálsdóttir T, Fitzgerald D, Rubin S, Capaldo M, Maugeri M, Leitass A, Bukantis A, Aberfeld R, Van Engelen AFV, Forland E, Mietus M, Coelho F, Mares C, Razuvaev V, Nieplova E, Cegnar T, López JA, Dahlström B, Moberg A, Kirchhofer W, Ceylan A, Pachaliuk O, Alexander LV, Petrovic P. 2002. Daily dataset of 20th century surface air temperature and precipitation series for the European climate assessment. *International Journal of Climatology* **22**: 1444–1453. DOI: 10.1002/joc.773

Lawrimore JH, Menne MJ, Gleason BE, Williams CN, Wuertz DB, Vose RS, Rennie J. 2011. An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. *Journal of Geophysical Research* **116**: D19121. DOI: 10.1029/2011JD016187

Li J, Zeng Q. 2002. A unified monsoon index. *Geophysical Research Letters* **29**: 1151–1154. DOI: 10.1029/2001GL013874

Lu J, Delworth TL. 2005. Oceanic forcing of the late 20th century Sahel drought. *Geophysical Research Letters* **32**: L22706. DOI: 10.1029/2005GL023316

Mannaerts CM, Gabriels D. 2000. Rainfall erosivity in Cape Verde. *Soil and Tillage Research* **55**: 207–212. DOI: 10.1016/S0167-1987(00)00104-5

Martín JL, Bethencourt J, Cuevas-Agulló E. 2012. Assessment of global warming on the island of Tenerife, Canary Islands (Spain). Trends in minimum, maximum and mean temperatures since 1944. *Climatic Change* **144**: 343–35. DOI: 10.1007/s10584-012-0407-7

McSweeney C, Lizcano G, New M, Lu X. 2010. The UNDP climate change country profiles. *Bulletins of the American Meteorological Society* **91**: 157–166. DOI: 10.1175/2009BAMS2826.1

Overland J, Rodionov S, Minobe S, Bond N. 2008. North Pacific regime shifts: definitions, issues and recent transitions. *Progress in Oceanography* **77**: 92–102. DOI: 10.1016/j.pocean.2008.03.016

Peng S, Robinson WA, Li S, Hoerling MP. 2005. Tropical Atlantic SST forcing of coupled North Atlantic seasonal responses. *Journal of Climate* **18**: 480–496. DOI: 10.1175/JCLI-3270.1

Peterson TC, Vose RS. 1997. An overview of the Global Historical Climatology Network temperature database. *Bulletins of the American Meteorological Society* **78**(12): 2837–2849. DOI: 10.1175/15200477(1997)078 < 2837:AOOTGH > 2.0.CO;2

Pettitt AN. 1979. A nonparametric approach to the change-point problem. *Journal of the Royal Statistical Society. Series C (Applied Statistics)* **28**: 126–135.

Polyakova EI, Journel AG, Polyakov IG, Bhatt US. 2006. Changing relationship between the North Atlantic Oscillation and key North Atlantic climate parameters. *Geophysical Research Letters* **33**: L03711. DOI: 10.1029/2005GL024573

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of SST, sea ice and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research* **108**: 4407. DOI: 10.1029/2002JD002670

Salas JD. 1993. Analysis and modelling of hydrologic time series. In *Handbook of Hydrology*. McGraw-Hill: New York; 19.1–19.72.

Santos FD, Valente MA, Miranda PMA, Aguiar A, Azevedo EB, Tome AR, Coelho F. 2004. Climate Change Scenarios in the Azores and Madeira Islands. *World Resource Review* **16**: 473–491.

Scaife AA, Folland CK, Alexander LV, Moberg A, Knight JR. 2008. European climate extremes and the North Atlantic Oscillation. *Journal of Climate* **21**: 72–83. DOI: 10.1175/2007JCLI1631.1

Sperling N, Washington R, Whittaker RJ. 2004. Future climate change of the subtropical North Atlantic: implications for the cloud forests of Tenerife. *Climatic Change* **65**: 103–123. DOI: 10.1023/B:CLIM.0000037488.33377.bf

Sun J, Wang J, Yuan W. 2008. Decadal variations of the relationship between the summer North Atlantic Oscillation and middle East Asian air temperature. *Journal of Geophysical Research* **113**: D15107. DOI: 10.1029/2007JD009626,2008

Tokinaga H, Xie S-P. 2011. Weakening of the equatorial Atlantic cold tongue over the past six decades. *Nature Geoscience* 4: 222–226, http://dx.doi.org/10.1038/NGEO1078

Tomé AR, Miranda PMA. 2004. Precise linear fitting and trend changing points of climate parameters. *Geophysical Research Letters* **31**: L02207. DOI: 10.1029/2003GL019100

Torrence C, Compo GP. 1998. A practical guide to wavelet analysis. *Bulletins of the American Meteorological Society* **79**: 61–78. DOI: 10.1175/1520-0477(1998)079 < 0061:APGTWA > 2.0.CO;2

Walsh JE, Portis DH. 1999. Variations of precipitation and evaporation over the North Atlantic Ocean 1958–1997. *Journal of Geophysical Research* **104**: 16613–16631. DOI: 10.1029/1999JD900189

Wang C. 2002. Atlantic climate variability and its associated atmospheric circulation cells. *Journal of Climate* **15**: 1516–1536. DOI: 10.1175/1520-0442(2002)015 < 1516:ACVAIA > 2.0.CO;2

Wijngaard JB, Klein-Tank AMG, Konnen GP. 2003. Homogeneity of 20th century European daily temperature and precipitation series. *International Journal of Climatology* **23**: 679–692. DOI: 10.1002/joc.906

Wilks D. 1995. *Statistical Methods in the Atmospheric Sciences, an Introduction*. Academic Press: San Diego.

Yue S, Wang CY. 2002. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. *Water Resources Research* **38**(6): 1068. DOI: 10.1029/2001WR000861

Zhang Q, Xu CY, Chen X, Zhang Z. 2011a. Statistical behaviours of precipitation regimes in China and theirs links with atmospheric circulation 1960–2005. *International Journal of Climatology* **31**: 1665–1678. DOI: 10.1002/joc.2193

Zhang Q, Singh VP, Li J, Xiaohong C. 2011b. Analysis of the periods of maximum consecutive wet days in China. *Journal of Geophysical Research* **116**: D23106. DOI: 10.1029/2011JD016088