INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **36**: 1873–1886 (2016)
Published online 27 August 2015 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4466

Modelled and observed sea surface temperature trends for the Caribbean and Antilles

Juan Carlos Antuña-Marrero,[a]* Odd Helge Otterå,[b] Alan Robock[c] and Michel d. S. Mesquita[b]

[a] *Atmospheric Optics Group of Camagüey, Meteorological Institute of Cuba, Camagüey, Cuba*
[b] *Uni Research Climate, Bjerknes Centre for Climate Research, Bergen, Norway*
[c] *Department of Environmental Sciences, Rutgers University, New Brunswick, NJ, USA*

ABSTRACT: The ocean occupies 95% of the Caribbean's area and plays a leading role in the region's climate, thus making the sea surface temperature (SST) a very important regional climate index. This, in conjunction with the lack of a regionally consistent, quality-controlled surface temperature dataset increases the scientific value of using SST to characterize the regional climate and its trends. This study determines the magnitudes of the long-term SST trends in the Wider Caribbean (WC) and the Antilles. We overcome the presence of discontinuity points in the SST time series using the change point statistical technique. Annual mean SST trends combining the subperiods 1906–1969 and 1972–2005 are 1.32 ± 0.41 °C per century for the Antilles and 1.08 ± 0.32 °C per century for the WC. For the same regions during the subperiod 1972–2005, the corresponding trends are 1.41 ± 0.68 °C per century and 1.18 ± 0.49 °C per century, illustrating the warming intensification during the last four decades. A significant correlation is found between the SSTs in the Caribbean and Atlantic Multidecadal Oscillation (AMO) index, suggesting a potential link between Caribbean SSTs and the mechanisms governing the Atlantic basin-wide SSTs. Finally, the capabilities of two state-of-the-art coupled climate models, the Norwegian Earth System Model (NorESM1-M) and the Bergen Climate Model (BCM), to simulate SST in the Caribbean were tested. Both models produce an adequate simulation of the annual mean SST anomalies and SST seasonal cycle for the WC and the Antilles. The simulated annual and monthly mean SSTs are colder in the two models compared to the observations, a common feature among the majority of general circulation models participating in the Coupled Model Intercomparison Project Phase 5. However, despite these minor deficiencies both BCM and NorESM1-M are considered adequate for conducting SST simulations relevant for future climate change research in the Caribbean.

KEY WORDS climate; sea surface temperature; sea surface temperature trend; Caribbean; Atlantic Multidecadal Oscillation; Antilles

Received 25 October 2014; Revised 4 June 2015; Accepted 7 July 2015

1. Introduction

The Wider Caribbean (WC), here defined as the region from 5° to 35°N, and from 55° to 100°W (Figure 1), represents a key region of the Atlantic Ocean climate system. The warm ocean waters are home to key coral reef ecosystems, and provide the livelihood for millions of people (Djoghlaf, 2008). Furthermore, the warm ocean temperatures feed the recurring tropical storms and hurricanes that ravage the region. Higher sea surface temperatures (SSTs) produce more and more intense tropical cyclones (e.g., Wu *et al.*, 2010; Lloyd and Vecchi, 2011). Therefore, understanding the long-term changes in the WC SSTs is of prime importance for assessing potential impacts of climate change on ecosystems and tropical cyclones. However, until now there have been major gaps in our scientific understanding of WC climate variability and climate change (CANARI, 2008), in particular due to a poor quality climatic record.

Most of the literature on the WC is based on future climate projections (e.g. Singh, 1997; Campbell *et al.*, 2011; Hall *et al.*, 2012; Karmalkar *et al.*, 2013). For instance, the recent Intergovernmental Panel on Climate Change report (IPCC, 2013) predicts for the Caribbean, with high level of confidence, increases in temperature between 0.7 and 2.4 °C by the end of the 21st century. For a similar period, with medium level of confidence, a decrease in precipitation is expected. The projections were made as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5), where 42 global climate models contributed simulations of future climate using the RCP4.5 scenario (Tables 14.1 and 14.2 of Christensen *et al.*, 2013). In this respect, WC precipitation is probably the variable that has been addressed most in the research literature, due to its noticeable impact on human and economic activities. The WC precipitation shows a broad range of variability both temporally and spatially, as indicated by a series of drought and flood events, with large societal and economic impacts (Laing, 2004; Small *et al.*, 2007; Méndez and Magaña, 2010).

In contrast, surface temperatures in the region show small seasonal variations (Taylor and Alfaro, 2005) and therefore have not been studied much. The SST and its

* Correspondence to: J. C. Antuña-Marrero, Atmospheric Optics Group of Camagüey, Meteorological Institute of Cuba, Marti # 263, Camagüey 70100, Cuba. E-mail: anadelia@caonao.cu; jcam45@gmail.com

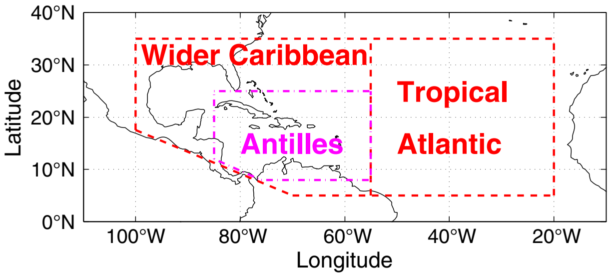

Figure 1. Regions selected for the present study: WC, Antilles and TA.

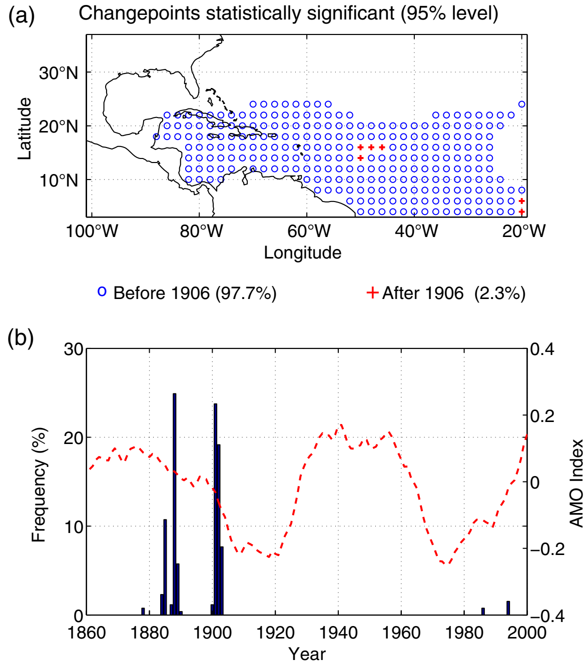

Figure 2. (a) Geographical and temporal distribution of change points for the period 1854–2005. (b) Frequency of occurrence over time of change points in SST grid-point series for the entire WC and TA region (see Figure 1), statistically significant at the 95% level.

long-term trend are both important variables for characterizing and identifying climate variability, and for determining fingerprints to establish the existence of climate change. For the period 1900–2008, positive SST trends in the range of 0.4–1.6 °C per century have previously been reported for the Tropics and subtropics (Deser *et al.*, 2010), and these values can be used for making gross estimates of the SST trends in the WC and the Antilles.

Sheppard and Rioja-Nieto (2005) reported a qualitative estimation of a rising trend in the measured SST for the Caribbean, although without determining its statistical significance. In addition, Sheppard and Rioja-Nieto (2005) provided a range of predicted SST trends for the 21st century. For the Gulf of Mexico and the western Caribbean Sea, a mean SST trend in the range of 0.05–0.27 °C per decade (determined for the minimum part of the last SST series section by the fitting of a piecewise linear model) was reported by Lluch-Cota *et al.* (2013). Although Lluch-Cota *et al.* made use of an SST dataset for the period 1910–2011, because of the statistical method used to detect recent trends, the reported trends across the region represent different periods covering from 10 to 60 or more years (Figure 2(b)). The SST trends from 1985 to 2009 in the Caribbean Sea and southeast Gulf of Mexico are determined using satellite data and show a regional mean value of 0.27 °C per decade. The first report of a heterogeneous spatial trends distribution in the Caribbean is very recent (Chollett *et al.*, 2012).The only report found in the literature of long term-temperature trends for a region of the WC, in this case the Antilles, uses the National Oceanic and Atmospheric Administration Extended Reconstructed Sea Surface Temperature (ERSST; Smith *et al.*, 2008) dataset. It describes a positive second-order trend for the Antilles SSTs, suggesting acceleration of the warming in recent years (Jury, 2011).

Peterson *et al.* (2002) analysed daily maximum and minimum monthly air temperature values in records of varying length, from 30 Caribbean surface stations, for the period 1958–1999. They determined that the extreme intra-annual temperature range decreased during this period, but that the trends were not significant. They also found that the maximum and minimum temperatures were both increasing, while it has been previously reported that the warming trends are higher for the monthly minimum temperatures than for the monthly maximum temperatures (Easterling *et al.*, 1997; Alexander *et al.*, 2006). Stephenson *et al.* (2008) incorporated new surface stations into the Peterson *et al.*'s (2002) dataset and compared time and space coincident maximum and minimum temperatures at 42 local stations and composites of SST grid points (1°) from the HadISST1 dataset. Common homogeneous periods were identified across the dataset, and trends of temperature extremes for the homogeneous period 1970–1992 reaffirmed the results of Peterson *et al.* (2002). A more recent study for the period 1961–2010 showed a warming in land surface temperatures, mainly associated with the increase of minimum temperatures (Stephenson *et al.*, 2014).

Naranjo-Diaz and Centella (1998) found a temperature increase of 0.5 °C in Cuba for the period 1950–1995, with particular warm periods in the 1980s and mid-1990s. They associated this trend with a strong positive trend in the minimum temperature series, with a mean warming of almost 1.4 °C. The trends in maximum temperatures were not significant, and consequently a decrease in the mean daily temperature range of almost 2 °C was observed for the same period. The authors considered those changes not to be sufficiently large or persistent enough to be considered evidence of climate change. Antuña *et al.* (1996) examined temperature trends based on 3-h temperature measurements from four stations in the province of Camagüey, Cuba, from the middle of the 1960s and lasting until 1994. A total of 60% of the trends were positive at the 90% significance level, ranging between 0.22 and 0.74 °C per century. However, there is not a unified, quality-controlled surface temperature regional dataset for the Caribbean suitable for conducting long-term surface temperature analysis. It is also not foreseen to be available in the near future. Quality-controlled information about the individual existing datasets for the different parts of the Caribbean is fragmentary or not available. There are no reports of validation of the surface temperature reanalysis datasets with surface temperature observations in the Caribbean that will support using surface temperature reanalysis data for long- and short-term surface temperature studies in the region. In particular, in the WC, islands have a land area of 240 000 km^2, with a sea-to-land ratio of about 20:1 (http://botany.si.edu/projects/cpd/ma/ma-carib.htm). The predominant existence of the sea in the WC determines its important role on the climate in the region and the relevance of SSTs.

The Atlantic Multidecadal Oscillation (AMO) represents the SST variability at multidecadal time scales in the North Atlantic (Kerr, 2000). It is represented by alternative periods of Atlantic Ocean SST warming and cooling in the latitude range between 70 or 60°N and the Equator, with a period of 60–80 years (Enfield *et al.*, 2001; Sutton and Hodson, 2005). From 1900 to 2008 during warm AMO phases, the cyclonic activity in the Caribbean increased with respect to the former cold AMO phases (Klotzbach, 2011). A connection between AMO and the precipitation in the Caribbean has been found when comparing observed and simulated precipitation anomalies during the warm AMO (1931–1960) and the cold AMO phase (1961–1990) (Sutton and Hodson, 2005). Statistically significant correlation at the 95% significance level between the means of maximum and minimum land surface temperatures for Caribbean stations has also been recently reported (Stephenson *et al.*, 2014). The El Niño/Southern Oscillation (ENSO) is one of the main drivers of temperature and rainfall variability in the Caribbean on inter-annual time scales, as has been shown by several recent studies (e.g. Jury and Gouirand, 2011; Gouirand *et al.*, 2012). However, as this study will focus on decadal trends in the Caribbean, the role of ENSO will not be addressed further.

In summary, existing climatological information of Caribbean temperatures is inhomogeneous both in space and in time, obtained mainly from local station records with different time and space scales, with different homogeneity and completeness and using a variety of region definitions. Because of the very few good land-based temperature records available and the particular relevance of SSTs for this region, the main goal of this study is to produce a consistent climatological analysis of SST trends for the Caribbean using a state-of-the-art global dataset. Next, the correlation between SSTs and AMO is tested. We use the SST record to evaluate simulations by two state-of-the-art coupled climate models, the Norwegian Earth System Model (NorESM1-M) and the Bergen Climate Model (BCM). The NorESM1-M is part of the CMIP5 project and has been tested globally with reasonable results (e.g. Sillmann *et al.*, 2013). The BCM participated in the CMIP3 project and has been evaluated successfully to study the impact of volcanic forcing on the AMO (Otterå *et al.*, 2010). Both models will be broadly used as part of the ongoing climate research cooperation between Norway and Cuba, and this evaluation of the models for this region is a crucial step in the work. Finally, we used BCM SST simulations for the period 2000–2099 for predicting potential future SST trends for the regions under study.

2. Materials and methods

2.1. Study regions

Figure 1 shows the regions selected for this study. These are composed of three main areas: the WC, the Tropical Atlantic (TA) and the Antilles. The WC region (5°–35°N and 100°–55°W) was determined following the common interpretation of Article 2 of the Cartagena Convention (http://www.cep.unep.org). The selection of the TA region (5°–35°N and 55–20°W) was made to facilitate a better model-data comparison. The third region, the Antilles (8°–25°N and 86°–54°W), was added adopting the criteria proposed by Jury (2011), because it covers all the insular countries in the Caribbean. Both for the WC and the Antilles, SST series from grid points south of the Pacific coast of Panama were removed from the analysis.

2.2. Datasets

The observational dataset consists of the ERSST, version 3b (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html) for the period 1854–2013. The ERSST version 3b is a globally reconstructed dataset extending from 1854 to the present, developed using state-of-the-art data merging techniques, but not including satellite-derived SSTs (Smith *et al.*, 2008). It is the latest improvement based on the International Comprehensive Ocean–Atmosphere Data Set (ICOADS; Woodruff *et al.*, 2010). It combines SST observations conducted irregularly in space and time worldwide, using different instruments and techniques. The ERSST data are provided as area-averaged monthly mean SSTs at 2° × 2° latitude–longitude grid points. In addition, we used an AMO SST index derived from the HadISST1 dataset, more specifically the smoothed dataset of Rayner *et al.* (2003).

2.3. Models

BCM consists of the Miami Isopycnic Coordinate Ocean Model (MICOM; Bleck *et al.*, 1992) coupled with the atmospheric model Action de Recherche Petite Echelle Grande Echelle/Integrated Forecast System (ARPEGE/IFS; Déqué *et al.*, 1994) and a dynamic–thermodynamic sea ice model (GELATO; Salas-Melia, 2002). BCM has 2.8° latitude and longitude resolution and 31 vertical levels from the surface up to 10 hPa. To better resolve the equator-confined dynamics, the meridional resolution gradually increases to 0.8° in the Tropics. The outputs were interpolated to 2° latitude and longitude resolution for the present study. Generally, the model reproduces the main precipitation patterns, including those associated with the mid-latitude storm tracks and the continental monsoons. However, there is a general tendency to underestimate the amount of precipitation compared to the observations, especially over the ocean (Otterå *et al.*, 2009). In addition, the ENSO variability in the model peaks around 2 years rather than the observed 3- to 7-year band, and is rather weak compared to the observations (Otterå *et al.*, 2009). More details on the large-scale circulation features and natural variability modes in the model can be found in the study by Furevik *et al.* (2003), with further information about the present version provided by Otterå *et al.* (2009).

In this study, we use historical ensemble runs covering the period 1850–1999, which incorporated natural (solar and volcanic) and anthropogenic (well-mixed greenhouse gases and tropospheric sulphate aerosols) forcing factors (Otterå *et al.*, 2010). In addition, available BCM simulations for the A1B, similar to the RCP 6.0 AR5 scenario (business as usual), and E1, similar to the RCP 2.6 AR5 scenario (low CO_2 emissions) for the period 2000–2099, were used for determining the future projections of the SSTs for the region of study (Johns *et al.*, 2011).

NorESM has been developed through a large national collaborative effort involving many research institutions in Norway and has participated in the recent CMIP5. NorESM is partly based on a recent version of the community model from the National Center for Atmospheric Research (NCAR). The atmosphere module is thus the Community Atmosphere Model version 4 (CAM4), and the land module is the Community Land Model (CLM). In NorESM, the ocean module is an updated version of MICOM. This ocean module is coupled to the Community Sea-Ice Model (CSIM/CICE). The model improves the modelling of tropical deep convection resulting in reproducing characteristic features of the Madden-Julian Oscillation (Subramanian *et al.*, 2011). However, NorESM also has limitations for the simulations in the tropical region, including an overestimation of the magnitude of tropical precipitation compared to observations. It also produces a double Inter-tropical Convergence Zone (ITCZ), a problem that has long been a common error among climate models (Bentsen *et al.*, 2013). For the present study with NorESM1-M, a medium resolution version was used. The atmospheric and land components of the model have a horizontal resolution of 1.9° in latitude by 2.5° in longitude, and the atmosphere has 26 levels up to 2.9 hPa. The horizontal resolution of the oceanic component of the model is 1.125° in latitude and longitude, with 53 layers. Historical ensemble runs from this model for the period 1850–2005 were available for the present study. A general description of the model and its large-scale circulation features is given by Bentsen *et al.* (2013) and Iversen *et al.* (2013).

To evaluate the factors affecting SSTs in the models we used SST, surface currents and latent heat fluxes (LHFs) from available observational data for the region. For the SST and LHF, we have used the TropFlux dataset (Praveen Kumar *et al.*, 2012). TropFlux is largely derived from a combination of ERA-Interim re-analysis data for turbulent and long-wave fluxes, and International Satellite Cloud Climatology Project (ISCCP) surface radiation data for shortwave flux. TropFlux uses bias and amplitude-corrected ERA-Interim fluxes. All bias corrections are derived based on comparisons with Global Tropical Moored Buoy Array data (Praveen Kumar *et al.*, 2012). The observed surface currents are taken from the Global Ocean Data Assimilation System (GODAS). GODAS is a real-time ocean analysis and a reanalysis. It is used for monitoring, retrospective analysis and for providing oceanic initial conditions for the NCEP climate forecast system. GODAS data are available from the NOAA/OAR/ESRL, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/.

2.4. Methods

SST monthly and annual area-averaged means were calculated both for the observed and simulated SST time series. Also SST annual means for each grid point of the observed and simulated SST time series were calculated. Linear trends for the annual and seasonal SSTs were calculated in both the observations and the model using the method of least squares, with adjustments, both for the area-averaged and grid-point values. Statistical significance was determined using a Student's *t*-test. All the significance tests in the following are at the 95% significant level. By taking into account the fact that the temperature series are regularly highly auto-correlated, the number of independent degrees of freedom was determined following Garrett and Toulany (1981). The adjusted standard errors for the SST trends were also calculated by taking into account the number of independent degrees of freedom (Wilks, 1995).

The ERSST dataset includes unresolved errors and inhomogeneities that could have an impact on its applications for climate research (Woodruff *et al.*, 2010). In particular in the case of the Antilles, before around 1925 there were fewer than 15 observations per grid point per year (Figure 1(b) of Jury, 2011). The same also happened during World War II and for a few years after. Also for the area between 60°N and 60°S the relation between the magnitude of the annual ERSST anomalies and its errors suggests that the dataset is more reliable after the 1940s (Figure 1 in http://www.ncdc.noaa.gov/ersst/).

Change point detection, a quantitative procedure, was selected to identify shifts in the observation SST time series that could be associated to the known limitations of the ERSST dataset (Gallagher *et al.*, 2013). Multiple change points were detected by subsegmenting. The whole series was tested and if any change points were detected, the method was subsequently applied to the resulting subsegments. No homogenization of the SST grid points data series was conducted. Change point detection was conducted for each SST grid point and the significance of each identified change point was determined. Change points indicate possible inhomogeneities in the time series, but could also be caused by strong climate changes, such as volcanic eruptions.

In addition, weighted trends for the period 1906–2005 were calculated from the trends for the two subperiods 1906–1969 and 1972–2005, using the number of years from each subperiod as the weight. Finally, correlations between the regional SSTs and the annual mean AMO SST index and between the annual mean SSTs from models and observations were calculated. The statistical significance was established considering the number of independent degrees of freedom (Garrett and Toulany, 1981).

3. Results

3.1. Geographical and temporal distribution of the grid-point SST series change points

Statistically significant change points are present in 49.3% of the grid points of the annual mean SST series in the entire WC and TA. For the WC and TA, there are change points in 47.7% and 50.7% of the grid points respectively, while for the Antilles the amount increases to 92.7%. Figure 2 shows the distribution of the statistically significant change points. All of them occur south of 25°N and 97.7% of the change points occur before 1906. From this figure, it is evident that the occurrence of statistically significant change points for the whole 1854–2005 period peaks during a negative rate of change (from warm to cold) of the AMO index.

Although change points could be caused by strong climate change as well as data inhomogeneities, because so many occurred before 1906, we find it convenient to choose 1906 for the beginning of our analysis. This also gives us 100 years of data for the period 1906–2005. Further analysis of this period was conducted, where the occurrence of change points inside this period was determined. Results showed the presence of statistically significant change points in 34.2% of the annual mean SST series for both the WC and TA together. The amount of statistically significant change points represents 64.2% of the Antilles, 33.2% of the WC and 35.1% of the TA.

The temporal frequency distribution of the change points, Figure 3, shows two main maxima. They are concentrated in the years 1925–1926, with 27.6% of all the cases, and in 1970–1971, with 59.1%. For our main area of interest, the Antilles, almost all the change points occur on and after that last pair of years. Based on these findings, we defined two subperiods for further analysis: 1906–1969 (64 years) and 1972–2005 (34 years). The highest frequency of occurrence of statistically significant change points for the 1906–2005 period occurs during a period of negative rate of change (from warm to cold) of the AMO, as pointed out for the period 1854–2005 above. The time between both sets of change points is approximately 65 years, matching the 60–80 years period of variability attributed to AMO (Sutton and Hodson, 2005).

The inclusion of the period before 1906 in the former analysis is based on the fact that there is no conclusive evidence that the first change point is caused solely by insufficient data during that period. Moreover, Figure 3 shows that the higher frequencies of occurrence of statistical significant change points, for the period 1906–2005, take place during the years 1925–1926 and 1970–1971. If we compare this result with the average number of available observations per grid point per year, as shown in Figure 1(b) from Jury (2011), we find that, those are years with higher relative amounts of observations. The years

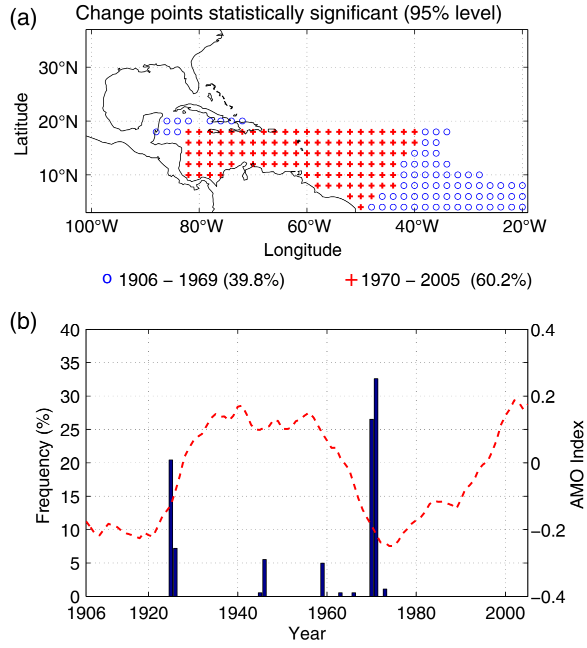

Figure 3. (a) Geographical and temporal distribution of change points for the period 1906–2005. (b) Frequency of occurrence over time of change points in SST grid-point series for the entire WC and TA region (see Figure 1), statistically significant at the 95% level.

with lower amounts of observations after 1906 predominantly occurred during World War I and II. However, the data show no statistically significant change points during World War I and only 6.1% of the statistically significant change points during World War II. This result could indicate that the effects of the low amounts of available observations for the ERSST data have been notably reduced because of the further improvements in the reconstruction of the dataset using state-of-the-art merging techniques (Smith *et al.*, 2008).

3.2. Observed SST trends for the studied regions

Figure 4 shows SST and trends for the period 1854–2005 and for the two subperiods 1854–1905 and 1906–2005 for the three regions selected in the current study. In all three regions, the linear trends for the period 1854–2005 and the subperiod 1906–2005 are positive with higher values in the latter period. For the period 1854–1905, however, the linear trends are negative. Annual mean values of the AMO SST index are also shown in Figure 4. It shows clearly that the change points occur during negative (cold) phases of the AMO and in particular during phases with a negative rate of change of the AMO. In both cases, the annual mean SSTs after the change points are lower than the ones before. The coincidence of the phases with negative rate of change of AMO with the lower annual mean SST after the change points suggests that the same physical mechanism, whatever it is, originates with the AMO and is causing the occurrence of the change points. Further research is necessary on this issue to determine the validity of this hypothesis. The correlation coefficients (r) for the three regions of interest in this study are all

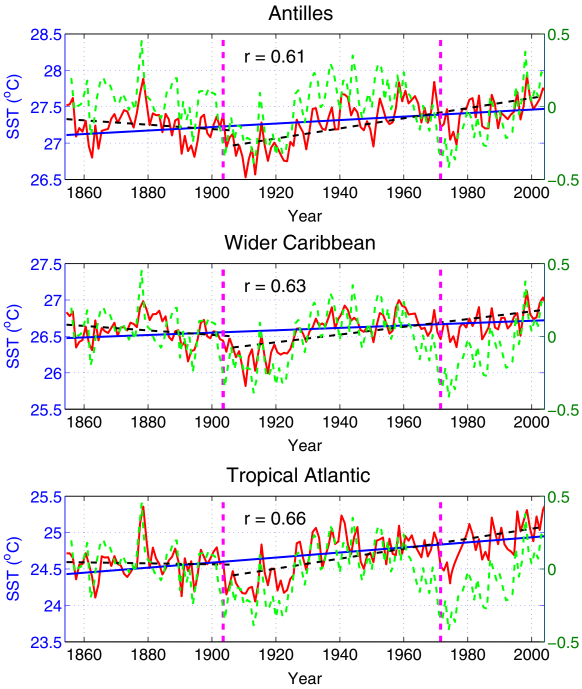

Figure 4. SST annual area average from observations (red solid lines) for the three regions (Figure 1) and AMO Index (green dashed lines) for the period 1854–2005. Least squares linear regression lines are shown for the entire period 1854–2005 (blue solid lines) and the sub-periods 1854–1905 and 1906–2005 (black dashed lines). Vertical magenta dashed lines denote the year of higher frequency of occurrence of the 95% level of statistical significance changepoints for the entire 1854–2005 period and for the sub-period 1906-2005. Correlation coefficients (r) are significant at the 95 % level after adjustment for the number of independent degrees of freedom using the method of Garrett and Toulany (1981).

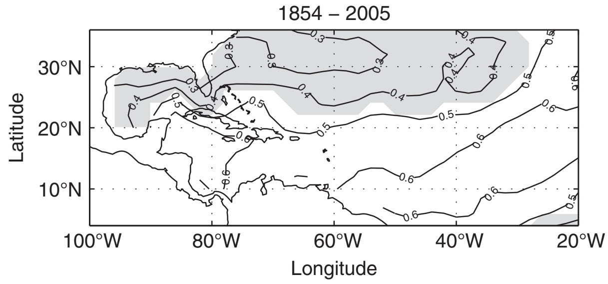

Figure 5. Contours of the SSTs *versus* AMO SSTs Index correlation coefficient (r). Shaded areas are trends not significant at the 95% level after adjustment for the number of independent degrees of freedom using the method of Garrett and Toulany (1981).

positive and statistical significant, with values slightly higher than 0.6.

Figure 5 shows the geographical distribution of the correlation coefficients between the annual mean values of the SSTs and the AMO SST index. The significance of the correlation coefficient values in both Figures 4 and 5 was tested after adjustment for the number of independent degrees of freedom (Garrett and Toulany, 1981). In general, significant correlation coefficients higher than 0.5 are predominately found in the Antilles while in the waters south of the United States and in the same latitude of the Atlantic, values are lower and not significant. This suggests a connection between the SSTs in the Caribbean and the mechanisms associated with the AMO's occurrence.

Table 1 shows that in all but three of the regions for the periods 1854–2005 and 1906–2005 all the trends are positive, on the order of the 1 °C per century, and statistically significant. For the period 1906–2005, the magnitudes of the SST trends are higher, with almost twice the values found for the period 1854–2005 for the Antilles and TA, and more than thrice the values found for the WC. The same table shows that in the case of the explained variance R^2, its magnitude almost doubled for the TA and increased three and four times for the Antilles and the WC, respectively, during 1906–2005 compared to the entire period. All three of the regions have steeper trends for the period 1906–2005 than for the entire period 1854–2005.

The adjusted standard errors represent the precision with which the fitting of the trend was determined, depending directly on the estimated standard deviation of the residuals. For the three regions and the three periods, all of the adjusted standard errors are of the same order of magnitude as the corresponding trends (Table 1). However, the magnitudes of the adjusted standard errors of the trends for the period 1906–2005 are half of the magnitudes of the trends for the three studied regions.

The period 1854–1905 shows a different pattern, with negative trends in the three regions. However, the trends are only statistically significant for the WC. The adjusted standard errors of the trends are all higher in magnitude than the trends during this period. Also for this period, the explained variance R^2 has very low magnitudes. Considering that the 1854–1905 period corresponds to a less reliable period of the ERSST dataset those results should be taken with particular caution.

Only the period 1906–2005, among the three periods analysed, shows robust positive trends in the order of 1 °C per century. That conclusion is supported by the fact that the trends are statistically significant and that the magnitude of the trends is double the magnitudes of the adjusted standard error.

The spatial distribution of the observed SST trends (Figure 6) for the 1854–2005 period shows that maximum values are about 0.4 °C per century in the central, northeast and southeast portions of the TA, with insignificant or even negative trends in the Gulf of Mexico. For the period 1854–1905, almost half of the region shows negative trends with values up to −0.9 °C per century covering the Gulf of Mexico, the waters east of Florida and the Greater Antilles, while positive values with maximum of 0.3 °C per century are present in the Lesser Antilles, the waters north of Venezuela and the Atlantic. For the 1906–2005 period, the pattern is similar to the period 1854–2005, but with larger trends in the southern portions of the region, with values up to 0.8 °C per century. In particular for the Antilles, for the period 1906–2005, the trends increase to the southeast from around 0.3 °C per century in the western portion of Cuba to 0.8 °C per century in the Lesser Antilles, near the coast of Venezuela. Non-significant SST trends

Table 1. Observed SST annual trends for the period 1854–2005 and the subperiods 1854–1905 and 1906–2005 for each of the studied regions.

	Period	Region		
		Antilles	Wider Caribbean	Tropical Atlantic
Linear SST trends and error (°C per century)	1854–2005	0.24 (0.18)	0.16 (0.15)	0.35 (0.17)
	1854–1905	−0.30 (0.44)	−0.31 (0.35)	−0.07 (0.44)
	1906–2005	0.70 (0.23)	0.53 (0.20)	0.67 (0.25)
R^2	1854–2005	0.14	0.10	0.27
	1854–1905	0.04	0.07	0.002
	1906–2005	0.45	0.40	0.42

In parenthesis are the trend standard errors, adjusted for the effective degrees of freedom. All the trends are statistically significant at the 95% significance level except the ones for the Antilles and the Tropical Atlantic for the subperiod 1854–1905. R^2 is the explained variance.

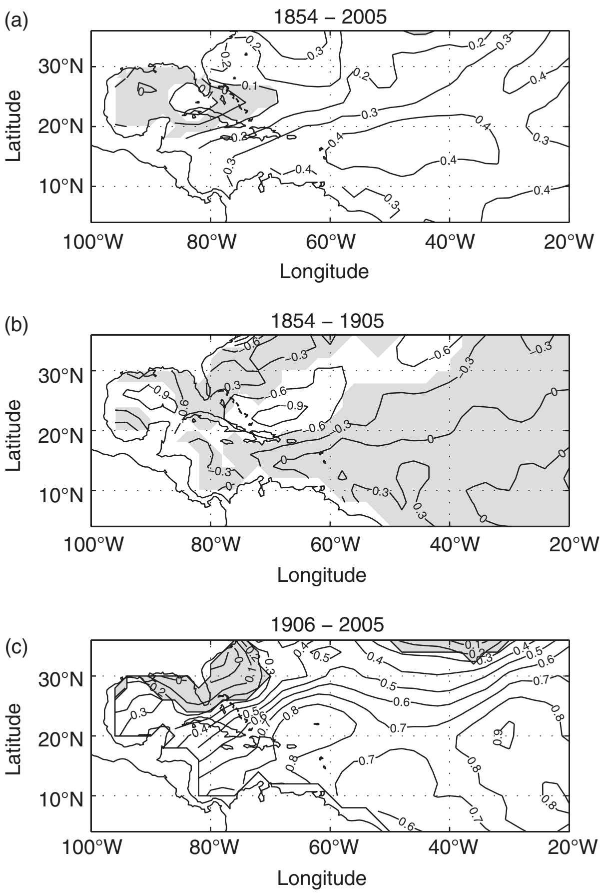

Figure 6. Distribution of observed SST annual mean linear trends (°C per century) for the three regions together. Trends not statistically significant have been shaded.

in the three regions decrease from 14% of the grid points for the 1854–2005 period to 7% for 1906–2005 period, while for the period 1854–1906 they represent 73% of the grid points with data. The heterogeneous pattern of the trend distribution in the Caribbean has been reported already (Chollett *et al.*, 2012; Lluch-Cota *et al.*, 2013). In particular, the cooling reported for the 1985–2009 period for the SSTs derived from satellite measurements in the high latitudes of the Caribbean has been attributed to the North American cold fronts transit across this region, and their increasing intensity and larger frequency in time (Melo-González *et al.*, 2000). That explanation could be also valid in the case of longer temporal scales like the ones in the current study.

The years 1970 and 1971 were excluded from the subperiods because they registered 20.4 and 24.1% of the significant change points for the 1906–2005 period. As shown in Table 2, all the SST trends for the subperiods 1906–1969 and 1972–2005 in all the three areas studied are higher than 1 °C per century. In particular for the Antilles, their magnitudes are 1.3 °C per century for the subperiod 1906–1969 and 1.4 °C per century for 1972–2005, with all the grid-point SST trends in that area statistically significant (Figure 7). This result agrees with recent reported trends for the Tropics and subtropics (Deser *et al.*, 2010). For both subperiods, the same pattern of geographical distribution remains, in particular the southeast increase of the SST trends for the Antilles.

The magnitudes of the adjusted standard trend errors for the subperiods 1906–1969 and 1972–2005 are shown in Table 2. They are all of the same order of magnitude as the trends (Table 2) similar to what was found for the 1906–2005 period. However, for the period 1906–1969 the magnitudes of the trends are about twice the magnitudes of the adjusted standard trend errors, while for the period 1972–2005 they are quite similar. The difference in the magnitudes of the adjusted standard trend errors between both subseries could be explained because of the decrease of degrees of freedom (and consequently of the adjusted degrees of freedom) from 64 for 1906–1969 to 32 for 1972–2005. It is supported by the fact that the adjusted standard trend errors depend directly on the estimated standard deviation of the residuals, and consequently on the inverse of the adjusted degrees of freedom,

The seasonal trends for the whole period 1854–2005 show almost no variation between the different seasons for the three regions, with positive and significant trends for all regions (Table 3). For the subperiod 1854–1905, insignificant negative trends are present in the Antilles and WC for all the seasons reaching the maximum absolute value in summer for the Antilles and in autumn for the WC. In the same subperiod for the TA no trend is found for the summer, with negative trends for the spring and autumn and positive for the winter. For the 1906–2005 period, statistically significant trends are found for all seasons. However, in contrast to the former two periods, for 1906–2005 a clear summer maximum is achieved in all

Table 2. Observed SST trends (°C per century) for the subperiods 1906–1969 and 1972–2005.

	1906–1969		1972–2005		1906–2005
	Trend	GST (%)	Trend	GST (%)	Trend
Antilles	1.27 (0.54)	100	1.41 (1.40)	97.7	1.32 (0.82)
Wider Caribbean	1.03 (0.47)	99.3	1.18 (1.20)	88.0	1.08 (0.71)
Tropical Atlantic	1.02 (0.60)	95.1	2.08 (1.55)	100	1.39 (0.91)

All the trends are statistically significant at the 95% significance level. In parenthesis are the trend standard errors (°C per century), adjusted for the effective degrees of freedom. The percent of grid-point significant trends (GST) statistically significant is also listed. The columns below the label '1906–2005' are the weighted mean of the entire period 1906–2005.

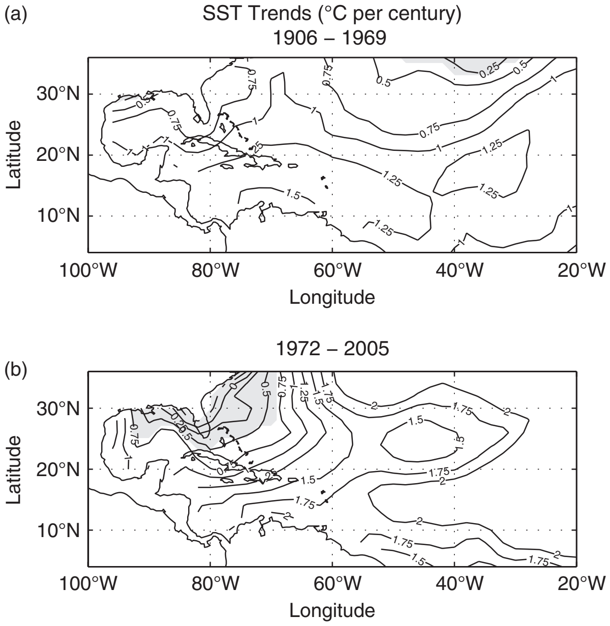

Figure 7. Distribution of observed SST annual mean linear trends (°C per century) for the three regions together. Trends not statistically significant have been shaded.

the three regions, on the order of 0.7 °C per century, while minimum trends are found mainly in autumn. In the case of the two subperiods 1906–1969 and 1972–2005 (Table 4), trends are on the order of 1.0 °C per century, with higher values during the second period and maximum trends occurring in summer for both the Antilles and the WC. The minimum trends for those regions are found in winter and in spring for the 1906–1969 and the 1972–2005 periods, respectively. For the TA, the maximum trends occur in spring and autumn for the 1906–1969 and 1972–2005 periods respectively, while the minimum trends occur in autumn and spring for the same periods.

The last three columns in Table 4 contain the weighted trends for each region for each season, calculated by averaging the trends for the periods before and after the change point, and weighting them by the length of each time series. They are all an order of magnitude higher than the trends in the last three columns of Table 3, calculated for each region for each season using the entire SST series 1906–2005. If the change points were produced due to natural causes, the trend for the whole series would be less reliable (lower correlation coefficients) and therefore less useful for predicting the future temperatures than the last piece of the series 1972–2005 (after the change point) or than the weighted trend. In that sense, when considering the presence of the statistically significant change points in the entire 1906–2005 SST series, the weighted trends are better suited to forecast the future values of the SSTs in the WC and the Antilles.

Based on the comparison of the occurrence of statistically significant change points with respect to the AMO index, as shown in Figure 4, we may consider the hypothesis that the AMO negative (cold) phase by some mechanism 'resets' the level of the SST, causing a jump in the SST time series as revealed by the change points. After that reset, the potential processes and mechanisms associated with the atmosphere–ocean interaction and its response to the changes in the climate keep acting in the region, producing again positive trends in the SSTs. We determine the effect of all those processes and phenomena on SSTs during the 1906–2005 period, by calculating the weighted trends from the two subperiods (Table 4, last three columns). The maximum trend values of 1.47 °C per century and 1.39 °C per century occur in summer for the Antilles and WC, respectively, while the minima occur in winter with magnitudes of 1.15 °C per century and 0.94 °C per century, respectively. For the TA, the maximum trend value occurs in winter (1.5 °C per century) and the minimum in autumn (1.33 °C per century).

4. Comparison of climate model SST simulations with the ERSST

Monthly mean SSTs for the period 1854–2005 from ERSST, BCM (five ensemble members) and NorESM1-M (three ensemble members) are shown in Figure 8. Both models reproduce the monthly mean SST distributions of maximum and minimum shown in the observed seasonal cycle. However, in general both models produce colder values for the three regions. The exception is the BCM for the TA, which matches exactly the magnitudes of the monthly mean SSTs from observations. NorESM1-M-simulated monthly mean SSTs have the largest differences with respect to the observations.

Both BCM and the NorESM1-M simulate colder SSTs for the three regions (Figure 9). This result is not surprising because it is well known that general circulation models (GCMs) tend to underestimate the SSTs

Table 3. Observed seasonal SST trends (°C per century) for the whole period 1854–2005 and the subperiods 1854–2005 and 1906–2005.

	1854–2005			1854–1905			1906–2005		
	Antilles	WC	TA	Antilles	WC	TA	Antilles	WC	TA
Winter	0.23	0.15	0.37	−0.08	−0.22	0.10	0.61	0.44	0.67
Spring	0.23	0.20	0.33	−0.39	−0.24	−0.17	0.71	0.56	0.66
Summer	0.22	0.20	0.35	−0.40	−0.23	0.00	0.79	0.72	0.72
Autumn	0.20	0.16	0.36	−0.31	−0.30	−0.10	0.55	0.45	0.64

None of the SST trends for the subperiod 1854–1905 are statistically significant at the 95% significance level.

Table 4. Observed seasonal SST trends (°C per century) for the subperiods 1906–1969 and 1972–2005.

	1906–1969			1972–2005			1906–2005		
	Antilles	WC	TA	Antilles	WC	TA	Antilles	WC	TA
Winter	1.09	0.82	1.11	1.27	1.18	2.23	1.15	0.94	1.50
Spring	1.35	1.04	1.14	1.13	1.07	1.89	1.27	1.05	1.40
Summer	1.36	1.26	0.95	1.68	1.62	2.16	1.47	1.39	1.37
Autumn	1.12	0.96	0.79	1.53	1.22	2.34	1.26	1.05	1.33

The columns below the label '1906–2005' are the weighted mean of the whole period 1906–2005.

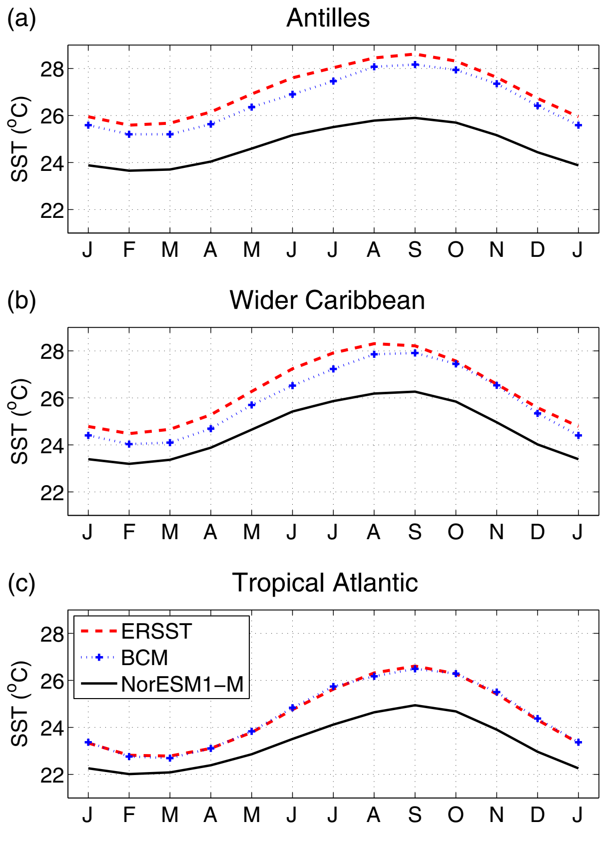

Figure 8. SST monthly mean seasonal cycles from observations and models for the three regions (Figure 1). BCM for the period 1854–1999 and both ERSST and NorESM1-M for the period 1854–2005.

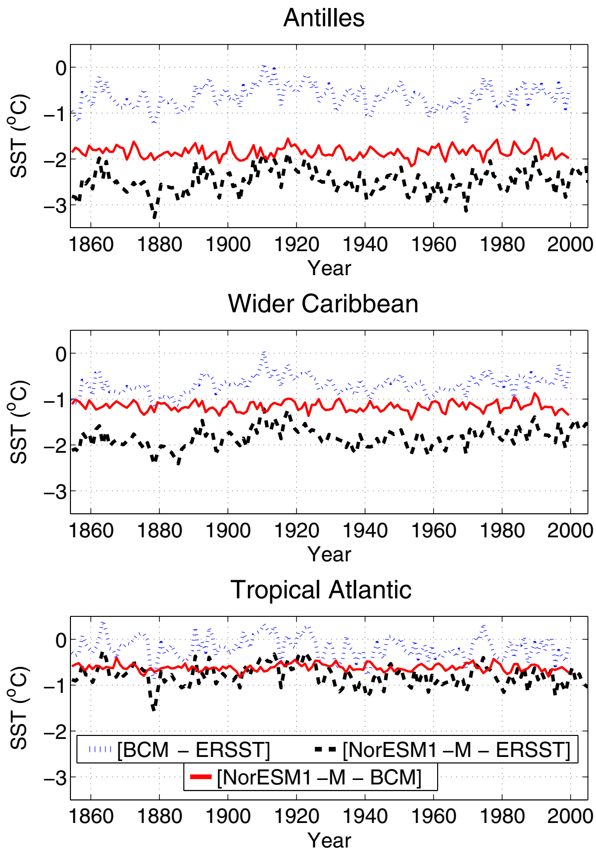

Figure 9. Model anomalies with respect to ERSST observations and differences between the two models.

in the tropical regions used in this study (Toniazzo and Woolnough, 2014). In particular for NorESM1-M, a recent CMIP5 model evaluation for the present climate showed that the NorESM1-M in particular underestimates most of the extreme temperature indexes selected (Sillmann *et al.*, 2013).

Observed and simulated SST, surface currents and LHFs are shown in Figure 10. In the observations, warm SSTs and high LHF are found in the Gulf Stream region along the coast of Brazil and into the Caribbean and the Gulf of Mexico (Figure 10(a) and (b)). Both BCM and NorESM1-M models show SST cold biases in the

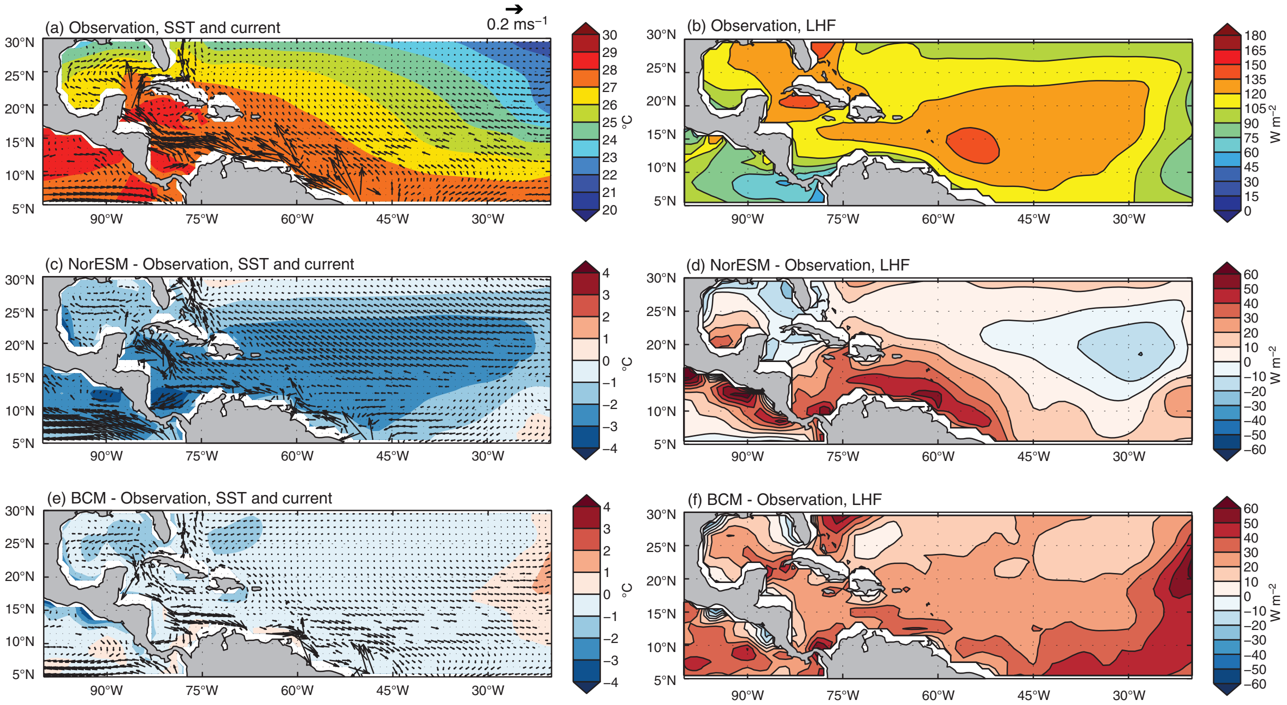

Figure 10. Observed and simulated SST (°C), surface currents (m s^{-1}) and LHF (W m^{-2}). (a) Observed SST from TropFlux (Praveen Kumar *et al.*, 2012) and surface current from GODAS for the period 1980–1999. (b) Observed LHF from the TropFlux dataset for the period 1980–1999. (c) Simulated difference from observations (model minus observations) in SST and surface currents for a three-member ensemble of historical NorESM runs for the period 1980–1999. (d) Same as (c), but for LHF. (e) Simulated difference from observations (model minus observations) in SST and surface currents for a 5-member ensemble of historical BCM runs for the period 1980–1999. (f) Same as (e) but for LHF.

Caribbean (Figure 10(c) and (e)). However, while the NorESM shows large (~2 °C) biases covering most of the WC region similar to other models (e.g. Liu *et al.*, 2012), BCM shows much smaller biases restricted only to the northwest section of the Gulf of Mexico. NorESM shows intensified ocean currents along the coast of Brazil, likely caused by too strong trade winds (not shown), and associated higher LHFs (Figure 10(c) and (d)). In BCM, on the other hand, the warm currents are weaker than observed (Figure 10(e)). The simulated higher LHFs in BCM (Figure 10(f)) are thus likely caused by other mechanisms than overestimated strength of the trade winds.

Figure 11 shows time series of the model simulations, after adjusting for their biases, as compared to the observations. In general, the SST anomalies from both models do an excellent job of simulating the observed anomalies, but both of them fail to represent high-frequency cooling and warming events. This is to be expected. The model output is smoother than observations partly due to the averaging of several ensemble members. There are, however, large discrepancies in the years surrounding the World War I, which may be due to data inadequacies. Although NorESM1-M includes both aerosol direct and indirect effects and BCM only includes the aerosol direct effect, the differences with respect to ERSST are very similar for both of them (Figure 9) and worse in magnitude for NorESM1-M than for BCM.

Table 5 quantifies the model results, and shows that for both models the SST trends and the R^2 increased slightly between the first and second periods, in contrast with the results shown in Table 1 for the observations. Because the observations for the period after 1906 SST are better, we consider the trends for that period a better representation of the real SST trends for all the three regions. For the period 1854–1906, the observed annual trends agree in general with models, but, both the magnitude of the SST annual area-averaged trends and R^2 are half or less than the magnitudes in the period 1906–2005. Both models show the same magnitudes of estimated SST change in both periods for all the three regions (Table 2). Compared to observations (Table 1) the models have larger trends for the period 1854–2005 and smaller for 1906–2005. The adjusted standard trend errors in the two models are about half of the values found for the trends (Table 5). The one exception is the BCM simulation for the period 1906–1999, where the adjusted trend error and the trend are of similar magnitude.

Figure 12 shows the spatial distribution of the simulated SST trends. For the BCM, both periods end in 1999 instead of 2005. In general, both models show maximum SST trends in the southeast of the TA, minima in the northeast, and secondary minima around most of the coast and the Gulf of Mexico for both periods. They match the pattern of maxima and minima in SST observations (Figure 4) better for the period 1906–2005 than for the whole period 1854–2005. The models have a secondary maximum in the northern section of the Antilles extending approximately over Cuba, Dominican Republic and Jamaica, which is not present in observations.

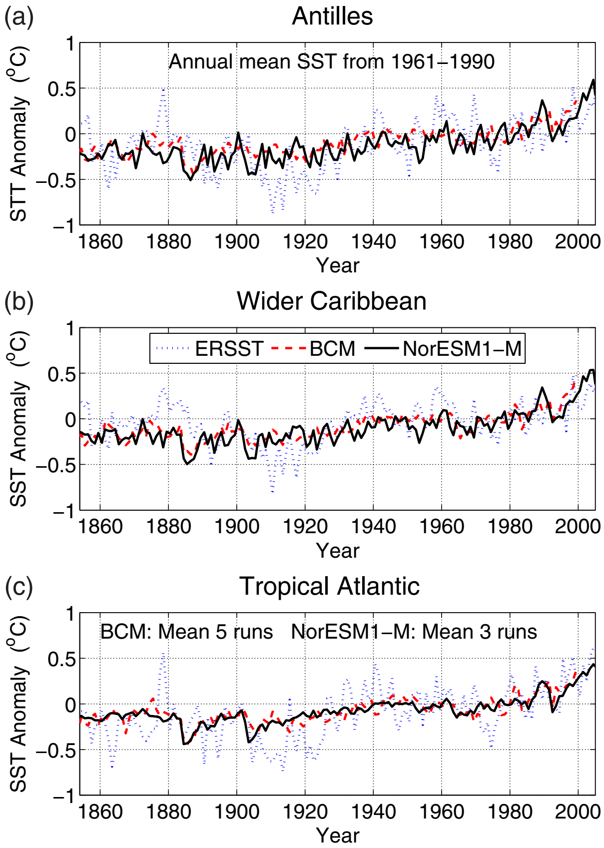

Figure 11. Annual SST annual mean anomalies with respect to the respective mean SST value for the period 1961–1990 for the SST observations (ERSST) and the SST model ensembles outputs from BCM and NorESM1-M. Model output is smoother than observations, due to the averaging of several ensemble members.

5. BCM model SST simulations for 2000–2099

The spatial distribution of the BCM-projected SST trends for the period 2000–2009 is shown in Figure 13, for both the E1 and A1B scenarios. For both scenarios, the trends are all statistically significant, showing an increasing trend southwards, with a similar patterns as the observed SST trends for all the analysed periods. The trends are higher in the A1B scenario than in E1 by an order of magnitude.

Table 6. BCM model forecast SST trends (°C per century) for the period 2000–2099 under the scenarios A1B and E1. All the trends are statistical significant. In parenthesis are the trend standard errors (°C per century), adjusted for the effective degrees of freedom.

	A1B	E1
Antilles	1.80 (0.41)	0.77 (0.38)
Wider Caribbean	1.76 (0.39)	0.86 (0.43)
Tropical Atlantic	1.72 (0.42)	0.70 (0.42)

For each of the scenarios, there are no significant differences in magnitudes of the trends between the different individual regions used in this study. However, a difference for the order of a magnitude is found between the two future scenarios (Figure 13.) The adjusted standard errors in the determination of the trends for all the regions and both scenarios are on the order of 0.1 °C per century. This is of the same order of magnitude as the trends for the E1 scenario, but one order of magnitude lower than for the A1B scenario.

When comparing the projected SST trends for the period 2000–2099 from Table 6 with the observed SST trends in Table 2 for the periods 1906–1969 and 1972–2005, we find that the best match for the projected trends occurs for the A1B scenario. The SST trends for these two periods and the projected SST trends are in the order of 1 °C per century. The observed SST-adjusted standard trend errors for the period 1972–2005 are an order of magnitude higher than for the projected trend for 2000–2099. However, for the period 1906–1969 the observed SST-adjusted standard trend errors are of the same order of magnitude as for the projected trend for 2000–2009.

The BCM-simulated SST trends for the periods 1854–1999 and 1906–1999 (see Table 5) are an order of magnitude lower than the projected SST trends for 2000–2009 (Table 6). However, the SST-adjusted standard trend errors are of the same order of magnitude. A similar pattern can be found by comparing the NorESM1-M

Table 5. SST trends (°C per century) for each region for the BCM and NorESM1-M simulations. In parenthesis are the trend standard errors (°C per century), adjusted for the effective degrees of freedom. ΔSST (°C) is the difference in the climate between the model and observations. For the BCM model, the ending year for both periods was 1999.

Model	Period		Antilles	Wider Caribbean	Tropical Atlantic
BCM	1854–1999	Trend	0.25 (0.11)	0.25 (0.11)	0.22 (0.12)
		R^2	0.54	0.54	0.43
		ΔSST	0.38	0.38	0.33
	1906–1999	Trend	0.39 (0.33)	0.40 (0.26)	0.38 (0.28)
		R^2	0.62	0.6	0.56
		ΔSST	0.39	0.39	0.37
NorESM1-M	1854–1999	Trend	0.31 (0.15)	0.29 (0.14)	0.25 (0.11)
		R^2	0.49	0.5	0.53
		ΔSST	0.46	0.44	0.38
	1906–1999	Trend	0.51 (0.24)	0.47 (0.22)	0.39 (0.17)
		R^2	0.59	0.59	0.64
		ΔSST	0.5	0.46	0.39

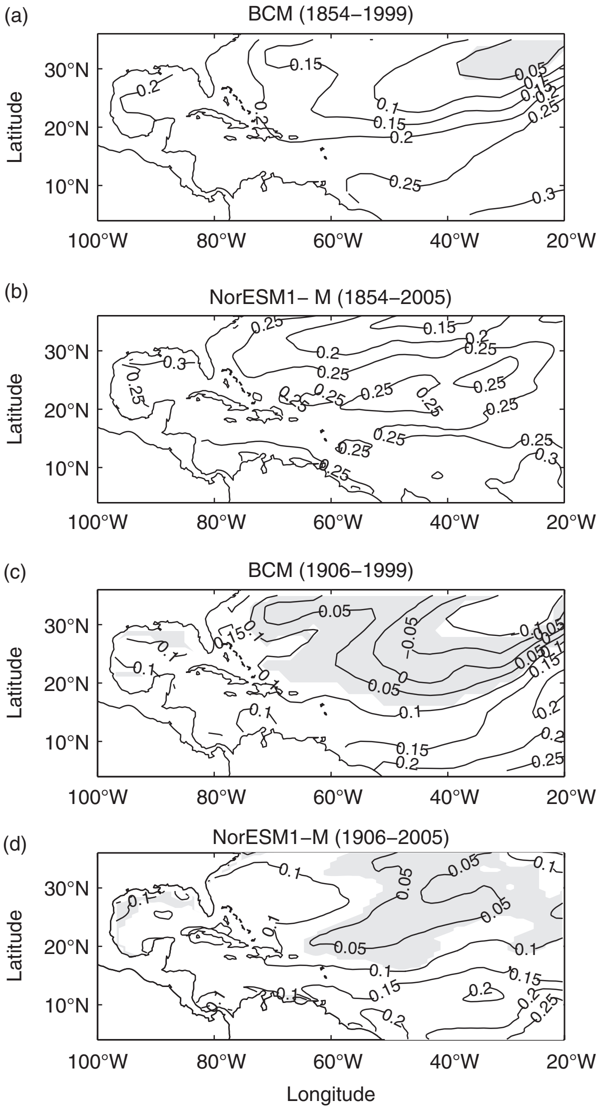

Figure 12. Linear trends (°C per century) of annual mean ensemble mean SST from BCM and NorESM1-M for the three regions together. Trends not statistically significant are shaded.

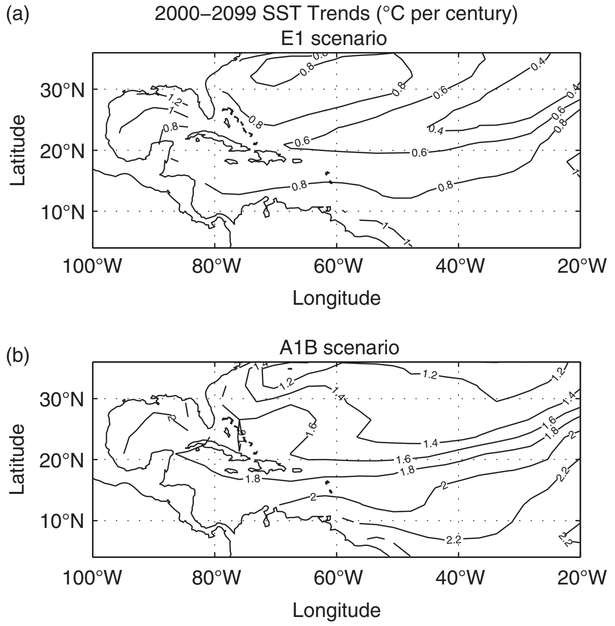

Figure 13. Distribution of BCM forecast SST annual mean linear trends (°C per century) for the three regions together, for the period 2000–2099. All the trends are statistically significant. Simulations conducted for the scenarios E1 and A1B.

SST trends and its adjusted standard errors for the periods 1854–2005 and 1906–2005 in Table 5 with the BCM projected SST trends its adjusted standard errors, for the period 2000–2099 in Table 6.

There is a notable degree of confidence in the BCM-projected SST trends for the period 2000–2099, for the Antilles and the WC, because they have the same signs and orders of magnitudes (for both A1B and E1) as the observed SST trends for the periods 1906–1969 and 1972–2005. In addition, the adjusted standard trend errors for the 2000–2099 projected SST trends and for the 1906–1969 observed SST trends are half of the magnitudes of the trends. Under the business-as-usual scenario the SST trends in the Antilles are in the range between 1.39 and 2.21 °C per century and for the WC between 1.37 and 2.15 °C per century. For the low CO_2 emissions scenario SST trends in the Antilles range between 0.39 and 1.15 °C per century while for the WC it will be 0.43 and 1.29 °C per century.

6. Summary

Determination of the long-term SST trends for the WC and the Antilles is affected by the presence of two statistically significant change points in the series, statistically significant, for the period 1854–2005. Taking into account the last two subperiods 1906–1969 and 1972–2005, defined by the change points, the weighted trends were calculated. The results show values of 1.32 °C per century for the Antilles and 1.08 °C per century for the WC. Considering that for the period 1972–2005 the trends were 1.41 °C per century and 1.18 °C per century for the Antilles and the WC, an intensification of the warming of the sea surface in both regions has been established.

Seasonally, for the period 1906–2005, higher SST trends are registered in summer, with maximum values of 1.68 and 1.62 °C per century for the Antilles and the WC in the period 1972–2005. Weighted SST trends for the summer during the period 1906–2005 were 1.47 °C per century for the Antilles and the 1.39 °C per century for the WC.

Geographically, the trends increase southeastward from around 0.75 °C per century around Cuba for the whole period 1906–2005 to values of 1.25 °C per century in the southernmost area of the Lesser Antilles during the subperiod 1906–1969 and 1.75 °C per century during 1972–2005. The main intensification of the warming is registered in the southernmost area of the Lesser Antilles and the Caribbean coast of Colombia and Venezuela.

The analysis for the Caribbean suggests that significant change points in the SST series are characterized by lower SST temperatures immediately after they occur. Their occurrence coincides with a negative rate of change of the AMO, potentially suggesting that both statistical features could be footprints of a common physical mechanism.

That hypothesis is reinforced by significant positive correlation coefficients (about 0.6) between SSTs and AMO.

Both the BCM and the NorESM1-M do an excellent job simulating annual mean SST anomalies in all the three regions studied. However, in the years surrounding the World War I discrepancies in the SST anomalies are large. The models also produce an adequate simulation of the SST seasonal cycle. Both the SST annual and monthly means in both models are colder than the observations, a feature typical of most of the GCMs in the CMIP5 ensemble. In that sense, BCM and NorESM1-M models are suitable to be used for research on Caribbean climate taking into account that limitation.

BCM projected future SST trends and their adjusted standard errors show a good agreement with observed SST trends and their adjusted standard errors for both the business as usual and low CO_2 emission scenarios. As a consequence, it is estimated that the SST trends for the WC will range between 1.37 and 2.15 °C per century under the business as usual scenario, and between 0.43 and 1.29 °C per century for the low CO_2 emissions scenario.

The results described above fill an existing research gap in the Caribbean region, pointing to intensification of the SSTs warming in the Caribbean in general, but with particular intensity in the southernmost part of the Lesser Antilles and the Caribbean coast of Colombia and Venezuela.

Acknowledgements

This work is supported by the project entitled, 'The Future of Climate Extremes in the Caribbean' (XCUBE) funded by the Direktoratet for samfunnssikkerhet og beredskap (DSB) on an assignment for the Norwegian Ministry of Foreign Affairs. This study is a contribution to the Centre for Climate Dynamics at the Bjerknes Centre for Climate Research. This project is part of the scientific cooperation between Norway and Cuba.

References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res.* **111**: D05109, doi: 10.1029/2005JD006290.

Antuña JC, Pomares I, Estevan R. 1996. Temperature trends at Camagüey, Cuba, after some volcanic eruptions. *Atmosfera* **9**: 241–250.

Bentsen M, Bethke I, Debernard JB, Iversen T, Kirkevåg A, Seland Ø, Drange H, Roelandt C, Seierstad IA, Hoose C, Kristjánsson JE. 2013. The Norwegian Earth System Model, NorESM1-M – Part 1: description and basic evaluation of the physical climate. *Geosci. Model Dev.* **6**: 687–720, doi: 10.5194/gmd-6-687-2013.

Bleck R, Rooth C, Hu D, Smith LT. 1992. Salinity-driven thermocline transients in a wind-and thermohaline-forced isopycnic coordinate model of the North Atlantic. *J. Phys. Oceanogr.* **22**: 1486–1505.

Campbell JD, Taylor MA, Stephenson TS, Watson RA, Whyte FS. 2011. Future climate of the Caribbean from a regional climate Model. *Int. J. Climatol.* **31**: 1866–1878.

CANARI. 2008. Climate trends and scenarios for climate change in the insular Caribbean. Technical Report No. 381, Caribbean Natural Resources Institute (CANARI), Laventille, Trinidad, W.I., 64 pp.

Chollett I, Müller-Karger FE, Heron SF, Skirving W, Mumby JP. 2012. Seasonal and spatial heterogeneity of recent sea surface temperature trends in the Caribbean Sea and southeast Gulf of Mexico. *Mar. Pollut. Bull.* **64**: 956–965.

Christensen JH, Krishna Kumar K, Aldrian E, An S-I, Cavalcanti IFA, de Castro M, Dong W, Goswami P, Hall A, Kanyanga JK, Kitoh A, Kossin J, Lau N-C, Renwick J, Stephenson DB, Xie S-P, Zhou T. 2013. Climate phenomena and their relevance for future regional climate change. In *Climate Change 2013: The Physical Science Basis – Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM. (eds). Cambridge University Press: Cambridge, UK and New York, NY.

Déqué M, Dreveton C, Braun A, Cariolle D. 1994. The ARPEGE/IFS atmosphere model: a contribution to the French community climate modeling. *Clim. Dyn.* **10**: 249–266.

Deser C, Phillips AS, Alexander MA. 2010. Twentieth century tropical sea surface temperature trends revisited. *Geophys. Res. Lett.* **37**: L10701, doi: 10.1029/2010GL043321.

Djoghlaf A. 2008. Perspectives on climate change from the convention on biological diversity. In *Climate Change and Biodiversity in the Americas*, Adam Fenech, Don Maciver, Francisco Dallmeier. (eds). Environment Canada: Toronto, Ontario, Canada, 25–34. ISBN: 978-1-100-11627-3.

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

Enfield DB, Mestaz-Nuñes AM, Trimble PJ. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.* **28**: 2077–2080.

Furevik T, Bentsen M, Drange H, Kindem IKT, Kvamstø NG, Sorteberg A. 2003. Description and validation of the Bergen Climate Model: ARPEGE coupled with MICOM. *Clim. Dyn.* **21**: 27–51.

Gallagher C, Lund R, Robbins M. 2013. Change point detection in climate time series with long-term trends. *J. Clim.* **26**: 4994–5006, doi: 10.1175/JCLI-D-12-00704.1.

Garrett C, Toulany B. 1981. Variability of the flow through the Strait of Belle Isle. *J. Mar. Res.* **39**: 163–189.

Gouirand I, Jury M, Sing B. 2012. An analysis of low and high frequency summer climate variability around the Caribbean Antilles. *J. Clim.* **25**: 3942–3952, doi: 10.1175/JCLI-D-11-00269.1.

Hall TC, Sealy AM, Stephenson TS, Kusunoki S, Taylor MA, Chen AA, Kitoh A. 2012. Future climate of the Caribbean from a super-high-resolution atmospheric general circulation model. *Theor. Appl. Climatol.* **113**: 271–287, doi: 10.1007/s00704-012-0779-7.

IPCC. 2013. *Climate Change 2013: The Physical Science Basis – Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM. (eds). Cambridge University Press: Cambridge, UK and New York, NY.

Iversen T, Bentsen M, Bethke I, Debernard JB, Kirkevåg A, Seland Ø, Drange H, Kristjansson JE, Medhaug I, Sand M, Seierstad IA. 2013. The Norwegian Earth System Model, NorESM1-M – Part 2: climate response and scenario projections. *Geosci. Model Dev.* **6**: 389–415.

Johns TC, Royer J-F, Höschel I, Huebener H, Roeckner E, Manzini E, May W, Dufresne J-L, Otterå OH, van Vuuren DP, Salas y Melia D, Giorgetta MA, Denvil S, Yang S, Fogli PG, Körper J, Tjiputra JF, Stehfest E, Hewitt CD. 2011. Climate change under aggressive mitigation: the ENSEMBLES multi-model experiment. *Clim. Dyn.* **37**: 1975–2003, doi: 10.1007/s00382-011-1005-5.

Jury MR. 2011. Long-term variability and trends in the Caribbean Sea. *Int. J. Oceanogr.* **2011**: Article ID 465810, doi: 10.1155/2011/465810.

Jury MR, Gouirand I. 2011. Decadal climate variability in the eastern Caribbean. *J. Geophys. Res.* **116**: D00Q03, doi: 10.1029/2010 JD015107.

Karmalkar AV, Taylor MA, Campbell J, Stephenson T, New M, Centella A, Bezanilla A, Charlery J. 2013. A review of observed and projected changes in climate for the islands in the Caribbean. *Atmosfera* **26**: 283–309.

Kerr RA. 2000. North Atlantic climate pacemaker for centuries. *Science* **288**(5473): 1984–1985, doi: 10.1126/science.288.5473.1984.

Klotzbach PJ. 2011. The influence of El Niño–Southern Oscillation and the Atlantic Multidecadal Oscillation on Caribbean tropical cyclone activity. *J. Clim.* **24**: 721–731, doi: 10.1175/2010JCLI3705.1.

Laing AG. 2004. Cases of heavy precipitation and flash floods in the Caribbean during El Niño winters. *J. Hydrometeorol.* **5**: 577–594.

Liu H, Wang C, Lee S-K, Enfield D. 2012. Atlantic warm-pool variability in the IPCC AR4 CGCM simulations. *J. Clim.* **25**: 5612–5628, doi: 10.1175/JCLI-D-11-00376.1.

Lloyd ID, Vecchi GA. 2011. Observational evidence for oceanic controls on hurricane intensity. *J. Clim.* **24**: 1138–1153.

Lluch-Cota SE, Tripp-Valdéz M, Lluch-Cota DB, Lluch-Belda D, Verbesselt J, Herrera-Cervantes H, Bautista-Romero J. 2013. Recent trends in sea surface temperature off Mexico. *Atmosfera* **26**: 537–546.

Melo-Gonzalez N, Müller-Karger FE, Cerdeira S, Pérez R, Victoria del Río I, Cárdenas P, Mitrani I. 2000. Near-surface phytoplankton distribution in the western Intra-Americas Sea: the influence of El Niño and weather events. *J. Geophys. Res. Oceans* **105**: 14029–14043.

Méndez M, Magaña V. 2010. Regional aspects of prolonged meteorological droughts over Mexico and Central America. *J. Clim.* **23**: 1175–1188.

Naranjo-Diaz LR, Centella A. 1998. Recent trends in the climate of Cuba. *Weather* **53**: 78–85.

Otterå OH, Bentsen M, Bethke I, Kvamstø NG. 2009. Simulated pre-industrial climate in Bergen Climate Model (version 2): model description and large-scale circulation features. *Geosci. Model Dev.* **2**: 197–212.

Otterå OH, Bentsen M, Drange H, Suo L. 2010. External forcing as a metronome for Atlantic multidecadal variability. *Nat. Geosci.* **3**: 688–694.

Peterson TC, Taylor MA, Demeritte R, Duncombe DL, Burton S, Thompson F, Porter A, Mercedes M, Villegas E, Semexant Fils R, Klein Tank A, Martis A, Warner R, Joyette A, Mills W, Alexander L, Gleason B. 2002. Recent changes in climate extremes in the Caribbean region. *J. Geophys. Res.* **107**(D21): doi: 10.1029/2002 JD002251.

Praveen Kumar B, Vialard J, Lengaigne M, Murty VSN, McPhaden MJ. 2012. TropFlux: air–sea fluxes for the global tropical oceans – description and evaluation. *Clim. Dyn.* **38**(7–8): 1521–1543.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108**(D14): 4407, doi: 10.1029/2002 JD002670.

Salas-Melia D. 2002. A global coupled sea ice–ocean model. *Ocean Model.* **4**: 137–172.

Sheppard C, Rioja-Nieto R. 2005. Sea surface temperature 1871–2099 in 38 cells in the Caribbean region. *Mar. Environ. Res.* **60**: 389–396.

Sillmann J, Kharin VV, Zhang X, Zwiers FW, Bronaugh D. 2013. Climate extremes indices in the CMIP5 multimodel ensemble – Part 1: model evaluation in the present climate. *J. Geophys. Res. Atmos.* **118**: 1716–1733, doi: 10.1002/jgrd.50203.

Singh B. 1997. Climate changes in the greater and southern Caribbean. *Int. J. Climatol.* **17**: 1093–1114.

Small RJO, de Szoeke SP, Xie S-P. 2007. The Central American midsummer drought: regional aspects and large-scale forcing. *J. Clim.* **20**: 4853–4873.

Smith TM, Reynolds RW, Peterson TC, Lawrimore J. 2008. Improvements to NOAA's historical merged land–ocean surface temperature analysis (1880–2006). *J. Clim.* **21**: 2283–2296.

Stephenson TS, Goodess CM, Haylock MR, Chen AA, Taylor MA. 2008. Detecting inhomogeneities in Caribbean and adjacent Caribbean temperature data using sea-surface temperatures. *J. Geophys. Res.* **113**: D21116, doi: 10.1029/2007JD009127.

Stephenson TS, Vincent LA, Allen T, Van Meerbeeck CJ, McLean N, Peterson TC, Taylor MA, Aaron-Morrison AP, Auguste T, Bernard D, Boekhoudt JRI, Blenman RC, Braithwaite GC, Brown G, Butler M, Cumberbatch CJM, Etienne-Leblanc S, Lake DE, Martin DE, McDonald JL, Ozoria Zaruela M, Porter AO, Santana Ramirez M, Tamar GA, Roberts BA, Sallons Mitro S, Shaw A, Spence JM, Winter A, Trotman AR. 2014. Changes in extreme temperature and precipitation in the Caribbean region, 1961–2010. *Int. J. Climatol.* **34**: 2957–2971, doi: 10.1002/joc.3889.

Subramanian AC, Jochum M, Miller AJ, Murtugudde R, Neale RB, Waliser DE. 2011. The Madden Julian Oscillation in CCSM4. *J. Clim.* **24**: 6261–6282, doi: 10.1175/JCLI-D-11-00031.1.

Sutton RT, Hodson DLR. 2005. Atlantic Ocean forcing of North American and European summer climate. *Science* **309**: 115–118.

Taylor M, Alfaro E. 2005. Climate of Central America and the Caribbean. In *The Encyclopedia of World Climatology*, Oliver J (ed). Springer Press: Dordrecht, The Netherlands, 183–189.

Toniazzo T, Woolnough S. 2014. Development of warm SST errors in the southern tropical Atlantic in CMIP5 decadal hindcasts. *Clim. Dyn.*, **43**(11): 2889–2913, doi: 10.1007/s00382-013-1691-2.

Wilks DS. 1995. *Statistical Methods in the Atmospheric Sciences*. Academic Press: San Diego, CA, 467 pp.

Woodruff SD, Worley SJ, Lubker SJ, Ji Z, Freeman JE, Berry DI, Brohan P, Kent EC, Reynolds RW, Smith SR, Wilkinson C. 2010. ICOADS release 2.5: extensions and enhancements to the surface marine meteorological archive. *Int. J. Climatol.* **31**: 951–967.

Wu L, Tao L, Ding Q. 2010. Influence of sea surface warming on environmental factors affecting long-term changes of Atlantic tropical cyclone formation. *J. Clim.* **23**: 5978–5989.

