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Seasonal and spatial heterogeneity of recent sea surface temperature trends in the Caribbean Sea and southeast Gulf of Mexico

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ABSTRACT

Recent changes in ocean temperature have impacted marine ecosystem function globally. Nevertheless, the responses have depended upon the rate of change of temperature and the season when the changes occur, which are spatially variable. A rigorous statistical analysis of sea surface temperature observations over 25 years was used to examine spatial variability in overall and seasonal temperature trends within the wider Caribbean. The basin has experienced high spatial variability in rates of change of temperature. Most of the warming has been due to increases in summer rather than winter temperatures. However, warming was faster in winter in the Loop Current area and the south-eastern Caribbean, where the annual temperature ranges have contracted. Waters off Florida, Cuba and the Bahamas had a tendency towards cooling in winter, increasing the amplitude of annual temperature ranges. These detailed patterns can be used to elucidate ecological responses to climatic change in the region.

1. Introduction

Global sea surface temperatures (SSTs) are rising. Over the past 150 years global mean SSTs have increased at an average of 0.04 °C decade^{-1} (Trenberth et al., 2007). Recent temperatures are changing at a much faster rate than in the past: since 1979, the global rate of warming has increased to 0.13 °C decade^{-1}, and is projected to continue to rise (Trenberth et al., 2007).

Changes in temperature are a general public concern (Patz et al., 2005; Solomon et al., 2007), but, from a biological perspective, consequences on the dynamics of marine organisms, brought about through changes to their physiology and phenology are of main significance. Increased temperatures can have either a positive or negative effect on physiological processes, depending on whether or not organisms are currently close to their thermal optimum for that particular function (Huey and Stevenson, 1979). Temperature regulates a large number of physiological functions in all organisms (Brown et al., 2004; Gillooly et al., 2001, 2002). Effects of increased temperatures on the physiology of marine organisms include increased developmental and growth rates (e.g., Gillooly et al., 2002; Lough and Barnes, 2000), decreased reproductive output (e.g., Philippart et al., 2003; Ruttenberg et al., 2005), increased prevalence of disease (e.g., Harvell et al., 2002; Sato et al., 2009), reduced planktonic life (e.g., Munday et al., 2009; O'Connor et al., 2007), and increased mortality (e.g., Gagliano et al., 2007; Rankin and Sponaugle, 2011).

The rate of warming determines the response of the organisms and their ability to acclimatize (Peck et al., 2009; Rezende et al., 2011). Although warming is occurring at a global scale, rates of warming differ according to the location, with some places even showing long-term cooling (Trenberth et al., 2007). Spatial heterogeneity in temperature trends has been observed at basin scales (Andersen et al., 2002; Demarcq, 2009; Good et al., 2007; Rayner et al., 2006; Strong et al., 2008) and also at regional scales (Peñaflor et al., 2009; Saulquin and Gohin, 2010). This variability implies that temperature-induced changes in marine organisms will likely vary dramatically, and sometimes in contrasting directions, within a given study area.

Changing temperatures can also affect the phenology of marine organisms, that is, the timing of life-history events. Seasonal changes in the temperature of the water affect the migration of many species (e.g., MacLeod et al., 2006; Solow et al., 2002) as well as the timing of gametogenesis and therefore spawning or nesting time (e.g., Baird et al., 2009; Colin, 1992; Olive, 1995). Changes in phenology of marine species in response to recent changes in temperature have already been reported in different parts of the globe (e.g., Philippart et al., 2003; Weishampel et al., 2004). Global and regional analyses of SST data have found considerable spatial

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heterogeneity in temporal properties of SST warming: while some areas are warming evenly all year long, others are warming only in particular seasons (López García and Camarasa Belmonte, 2011; Trenberth et al., 2007). Temporal (e.g., seasonal) differences in warming trends are likely to affect organisms differently. For example, if gametogenesis is closely linked to changes in temperature, its phenology might be only weakly modified if warming occurs outside the main reproductive season. On the other hand, increases of temperature in summer might be more likely to tip organisms towards upper lethal levels than if warming occurred at cooler times of the year.

To fully appreciate the impact of rising temperatures on organisms and ecosystems, we must first understand the scales of change involved. Here we examined overall and seasonal SST trends throughout the Caribbean Sea and south-eastern Gulf of Mexico. We used satellite imagery for the period 1985–2009 and a statistical method that takes into consideration the complexities of environmental time series (Weatherhead et al., 1998). Although previous studies of satellite-based SST trends have included the Caribbean in their analyses (Demarcq, 2009; Strong et al., 2000, 2008), our study is the first to resolve detailed spatial patterns in temperature trends within the Caribbean region. Further, previous studies have not assessed seasonal patterns in SST changes or employed statistical methods better suited for the detection of reliable trends in SSTs. Although our study is motivated by describing spatial and temporal patterns of changing SSTs, we anticipate that such trends will lead to the testing and generation of hypotheses across a wide range of fields because temperature has such a fundamental impact on biological function and ecosystem integrity.

2. Methods

2.1. Dataset

Satellites have supplied information about SST of the global oceans since the 1980s. To date, the National Oceanic and Atmospheric Administration (NOAA) Pathfinder Project (Kilpatrick et al., 2001) provides the longest consistent and continuous global SST dataset, with a very detailed spatial resolution (4 km). Trends in SST have been detected using Pathfinder data at global (e.g., Good et al., 2007; Lawrence et al., 2004; Strong, 1989; Strong et al., 2008) and regional (e.g., Ginzburg et al., 2008; Peñaflor et al., 2009; Saulquin and Gohin, 2010) spatial scales.

This study covers the Caribbean Sea, the south-eastern Gulf of Mexico, the Bahamas and Florida (8–28°N, 58–89°W, Fig. 1). We used the Pathfinder v5.0 SST data derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR: Casey et al., 2010; Kilpatrick et al., 2001). The spatial resolution was approximately 4 km for daily global images for 1985–2009. The Pathfinder SST accuracy is 0.1–0.5 °C (Kilpatrick et al., 2001). Weekly composites were constructed and data gaps (i.e., no valid data of quality level four or greater; Kilpatrick et al., 2001) were filled by interpolating in time and then by interpolating spatially following the approach described by Heron et al. (2010).

2.2. Statistical methods

A number of studies have examined trends observed in satellite SST data using linear methods (e.g., Andersen et al., 2002; Peñaflor et al., 2009; Strong et al., 2008), which allows a simple approximation to the magnitude of SST changes. However, some variability in the time series ought to be considered during trend detection, such as seasonality and serial correlation, which influence the magnitude and significance of the calculated trends (Weatherhead et al., 1998). By incorporating temporal autocorrelation, we account for issues such as an abnormally hot month being usually followed by another particularly hot month, a simple fact that violates the assumption of independence of most regression analyses and influences the precision of the trend estimates (Weatherhead et al., 1998). This approach for the detection of trends has been commonly applied to detect trends in environmental data (e.g., Boers and van Meijgaard, 2009; Zhang and Reid, 2010), but to date, it has only been used by Good et al. (2007) to assess changes in satellite SSTs.

Monthly means were calculated from the 25 year-long time series of SST and these were used for regression analyses. We estimated linear trends in SSTs following the approach proposed by Weatherhead et al. (1998). Monthly SSTs were fit to a non-linear model with the form:

$$\mathrm{SST}_t = \mu + S_t + \frac{\omega t}{12} + N_t \tag{1}$$

where SST at a given time t in months is a function of a constant term μ, a seasonal component S_t, a linear trend ω of rate °C year^{-1} and residuals, N_t, assumed autoregressive of order 1 (AR-1 autocorrelation form). The seasonal component (S_t) is described by:

$$S_t = \sum_{j=1}^{4} \beta_{1,j} \sin\frac{2\pi jt}{12} + \beta_{2,j} \cos\frac{2\pi jt}{12} \tag{2}$$

The residual variability (N_t) is described by:

$$N_t = \phi N_{t-1} + \epsilon_t \tag{3}$$

This way, the residuals at time t are a function of the residuals at time t-1 along with the noise (ε_t). The model used a generalized least squares fit and was fitted using the package nlme (linear and non-linear mixed effects) in R. Initial "guess" estimates for μ and ω were obtained through simple linear regression. We fixed an initial value of 1 for all β's.

The remaining variability ε_t was assumed to be random with standard deviation σ_ϵ. This variability, together with the autocorrelation parameter ϕ and the number of years of data, n, was used to calculate the error of the trend estimate (σ_ω):

$$\sigma_\omega = \frac{\sigma_\epsilon}{(1-\phi)n^{3/2}} \tag{4}$$

This implies that the precision of the trend is a function of the magnitude of the unexplained variability in the data, the autocorrelation of the noise, and the length of the time series (Weatherhead et al., 1998).

The number of years of data required to detect the trends described by Eq. (1) at the 95% confidence level was also calculated following Weatherhead et al. (1998):

$$n = \left[\frac{3.3\sigma_\epsilon}{|\omega|(1-\phi)}\right]^{2/3} \tag{5}$$

To assess trends in different seasons we divided the year into calendar seasons. This way, we defined winter as December–February, spring as March–May, summer as June–August and autumn as September–November. SST was averaged over these periods for each of the 25 years and the SST trend for each of the seasons was estimated using Eq. (6). This included similar parameters as Eq. (1) but excluded seasonal effects:

$$\mathrm{SST}_t = \mu + \omega t + N_t \tag{6}$$

While temporal autocorrelation is likely higher in monthly data than in the series of seasonal means, we expect temporal dependency continues to be an important issue at this temporal scale (e.g., Hinkelman et al., 2009).

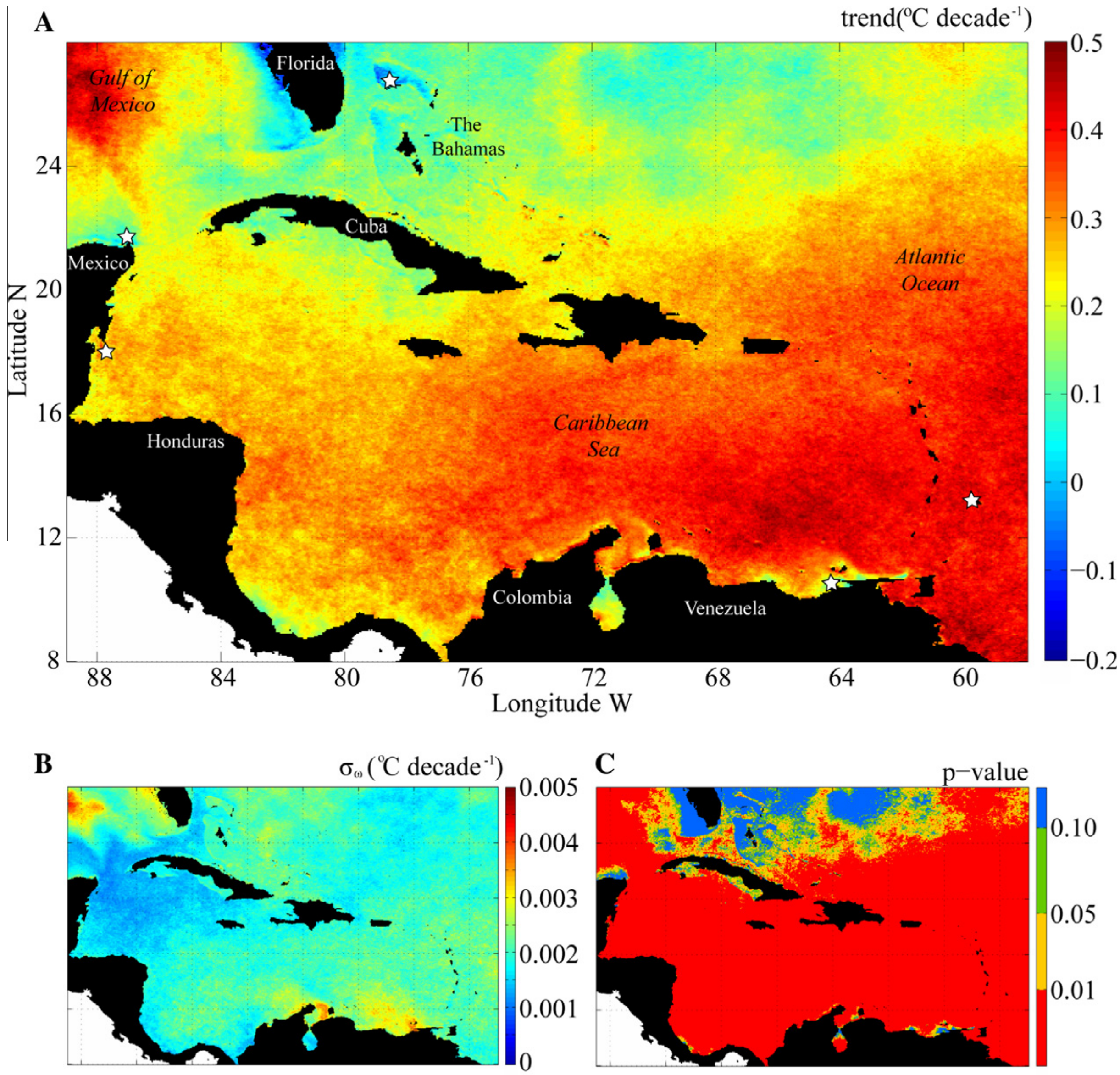

Fig. 1. (A) Decadal trends in average SST in the Caribbean; (B) associated standard deviation (Eq. (4)); (C) significance of the trend. Stars indicate the locations for Table 1 and Fig. 2.

Finally, we calculated long-term trends in annual temperature range: by subtracting the winter from the summer SST average for each year and measuring how this amplitude changed over 25 years. To this end, we used the same approach described by Eq. (6). Unless indicated, we report trends (ω) and associated errors (σ_ω : Eq. (4)) in °C decade^{-1}.

3. Results

3.1. Overall SST trends

The monthly time series of SSTs agree well with the non-linear model used (Table 1, Fig. 2). As might be expected, the constant term (μ) is higher for locations characterized by warmer SST regimes (e.g., Belize and Barbados). The model seems to accommodate time series of differing seasonal complexity, exhibiting annual (e.g., Northern Bahamas) or semi-annual (e.g., Barbados) components. Model residuals (not shown) do not display temporal patterns and, overall, the model could be considered appropriate for the data.

The average trend in SST over the Caribbean Sea and the south-eastern Gulf of Mexico was 0.29 °C decade^{-1} (including only significant values), with a range of −0.20–0.54 °C decade^{-1} (Fig. 1A). The study area showed spatially heterogeneous temperature trends (Fig. 1A). The trend estimates exhibited modest (<0.005 °C decade^{-1}) standard deviations across the basin (Fig. 1B). All significant trends ($p \leqslant 0.05$) were positive (Fig. 1). Warming was greatest in the tropical Atlantic and eastern Caribbean Sea (e.g., Barbados, Fig. 2A) and in the central Gulf of Mexico in the Loop Current region. However, temperature trends were moderate and significant throughout most of the centre and western Caribbean basin (e.g., Belize, Fig. 2B). Long-term trends were small and non-significant in shelf waters off Florida, Cuba and the Bahamas (Fig. 2C), in the upwelling area off the Yucatan Peninsula (Mexico, Fig. 2D) and in the southern Caribbean Sea along the coastal upwelling areas (Fig. 2E). Standard deviations of the trend estimates, which summarize the variability and autocorrelation of the noise (Eq. (4)), were higher in the upwelling areas of the southern Caribbean, as well as in the Loop Current region and the shelf waters off the western Florida shelf (Fig. 1B). Both the size and the standard deviation of the trend estimate contribute to the

Table 1
Non-linear random effects parameter estimates (Eq. (1)) and significance for the five locations marked with stars in Fig. 1 and plotted in Fig. 2. Note that the units of ω are annual (not decadal) trends in °C year^{-1}.

Parameter	Barbados		Belize		N. Bahamas		Yucatan		E. Venezuela	
	Value	*p*-value	Value	*p*-value	Value	*p*-value	Value	*p*-value	Value	*p*-value
μ	26.984	<0.001	27.422	<0.001	26.055	<0.001	26.092	<0.001	25.362	<0.001
ω	0.039	<0.001	0.024	<0.001	−0.005	0.567	0.004	0.559	0.014	0.198
$\beta 11$	−0.908	<0.001	−0.905	<0.001	−1.595	<0.001	−1.154	<0.001	−1.596	<0.001
$\beta 21$	−0.345	<0.001	−0.901	<0.001	−2.928	<0.001	−1.420	<0.001	−0.749	<0.001
$\beta 12$	−0.184	<0.001	−0.092	0.007	0.027	0.662	0.055	0.243	−0.258	<0.001
$\beta 22$	−0.365	<0.001	−0.255	<0.001	0.195	0.002	−0.193	<0.001	−0.543	<0.001
$\beta 13$	0.003	0.897	0.089	0.007	0.141	0.005	0.094	0.011	0.051	0.230
$\beta 23$	0.103	<0.001	0.115	<0.001	−0.025	0.610	0.048	0.201	0.085	0.047
$\beta 14$	0.011	0.602	0.000	0.987	0.024	0.563	−0.003	0.925	0.031	0.388
$\beta 24$	−0.064	0.003	−0.045	0.042	−0.047	0.263	−0.021	0.512	−0.110	0.002
ϕ	0.590		0.523		0.437		0.454		0.563	
σ_ε	0.441		0.416		0.721		0.550		0.710	

lack of significance in different areas. When the effect size is small significance will not be achieved. The same occurs in locations with highly variable SST patterns where the noise is greater, or in areas where autocorrelation is large.

3.2. Seasonal SST trends

Seasonal SST trends were larger than trends observed in the overall time series of monthly means (Figs. 1 and 3). In general, warming of summer and autumn SSTs was more intense than warming of winter and spring SST in the region (Fig. 3). Patterns in SST trends in spring and autumn show transition states between the summer and winter extremes. Positive SST trends in summer were significant in most of the study area (Fig. 3F) with an average of 0.33 °C decade^{-1} (Fig. 3E). A much decreased, non-significant summer warming was observed in the upwelling areas of Yucatan and the southern Caribbean Sea, as well as in the Lake Maracaibo (Venezuela) and the eastern Florida shelf.

Winter SST trends showed contrasting patterns in the Caribbean Sea and south-eastern Gulf of Mexico (Fig. 3A). The regional average was 0.18 °C decade^{-1}. However, many pixels showed non-significant trends ($p > 0.05$, Fig. 3B). Very fast warming of winter temperatures occurred in the interior of the Gulf of Mexico in the area dominated by the Loop Current (about 0.7 °C decade^{-1}), and in some areas of the south-eastern Caribbean. With these exceptions, warming in the region occurred at lower rates in winter than in summer. Near the coast, upwelling foci in the southern Caribbean showed non-significant warming in winter (Fig. 3B). North of the Yucatan Peninsula SST trends in upwelling and neighbouring non-upwelling areas were similar and non-significant. In shelf waters off Florida, the Bahamas and Cuba trends were the lowest for the study region, with a tendency towards winter cooling (−0.2 °C decade^{-1}, Fig. 3A), although most of these trends were non-significant.

These changes in summer and winter temperatures result in variations to annual temperature ranges depicted in Fig. 4. Decreases over time in seasonal temperature amplitude in the southern Caribbean Sea and in the Loop Current coincided with increases in winter temperatures (Fig. 3A). These changes are mostly non-significant. In contrast, there was a significant level of increase in the annual range in the western Caribbean and shallow shelf regions of the northern areas of the study region, mostly related to decreases in winter temperatures in those areas (Fig. 3A).

4. Discussion

4.1. SST trends in the Caribbean Sea and southeast Gulf of Mexico

The decadal warming rate calculated here for the wider Caribbean over the period 1985–2009 was 0.27 °C decade^{-1}. This rate is higher than that reported for the northern hemisphere for the period 1979–2005 by the Intergovernmental Panel on Climate Change in 2007 (0.19 ± 0.13 °C decade^{-1} from 1979 to 2005: Trenberth et al., 2007); nevertheless, it lies within the range of values estimated by two analyses of recent satellite SST data at higher spatial resolution than Trenberth et al., 2007 (Good et al., 2007; Strong et al., 2008). Using 4 km SST AVHRR data for the period 1985–2006, Strong et al. (2008) estimated rates of warming between 0.2 and 0.6 °C decade^{-1} in a few selected locations within the Caribbean basin. Good et al. (2007) estimated rates of warming for the entire basin of about 0.3 °C decade^{-1} for the period 1985–2004, based on AVHRR data at 2.5° spatial resolution.

There is high spatial heterogeneity in SST trends within the Caribbean Sea and the south-eastern Gulf of Mexico (Fig. 1). By examining the region using high spatial resolution data the effects of oceanographic features within the Caribbean basin (e.g., loop current) that would otherwise be averaged out may be observed, providing a more accurate representation of the warming trends. Such detailed variability provides a portrait of disturbance incidence in the region, being more relevant in an ecological context. This information could be used to understand perturbation incidence and the likely response of marine ecosystems within the area (Parmesan and Yohe, 2003; Root et al., 2003).

Summer warming has been more intense than winter warming in most of the Caribbean Sea and south-eastern Gulf of Mexico, which challenges some expectations (Parmesan and Yohe, 2003; Trenberth et al., 2007). In light of these results, predictions regarding expected changes in the phenology and physiology of Caribbean marine species should be revisited, as for example has been done by Von Holle et al. (2010) when assessing (unexpected) recent delays in seasonal flowering of Floridian plants related to decreased winter temperatures.

The long-term patterns of winter cooling observed in high-latitude areas, specifically coastal and shelf waters off Florida, Cuba and the Bahamas, can be related to the more intense and frequent passing of cold-air fronts from the North American continent (Melo-González et al., 2000; Roberts et al., 1982). The southward advection of these artic air-masses has been related to the downward trend of the North Atlantic Oscillation since the early 1990s (Wang et al., 2010), which has already negatively impacted marine ecosystems in the region (e.g., Kemp et al., 2011). These cooling trends are in sharp contrast with the fast-warming trends observed in the Loop Current, which transports warm waters from the Caribbean basin. The Loop Current is a surficial flow that joins the Yucatan and the Florida Currents, and it is active all year round (Johns et al., 2002). However, the SST signal of this current can only be detected during winter, when the thermal gradient of the Loop waters and the remaining waters of the Gulf of Mexico is pronounced enough to be seen at the surface (Bunge et al., 2002). *In situ* studies need to be

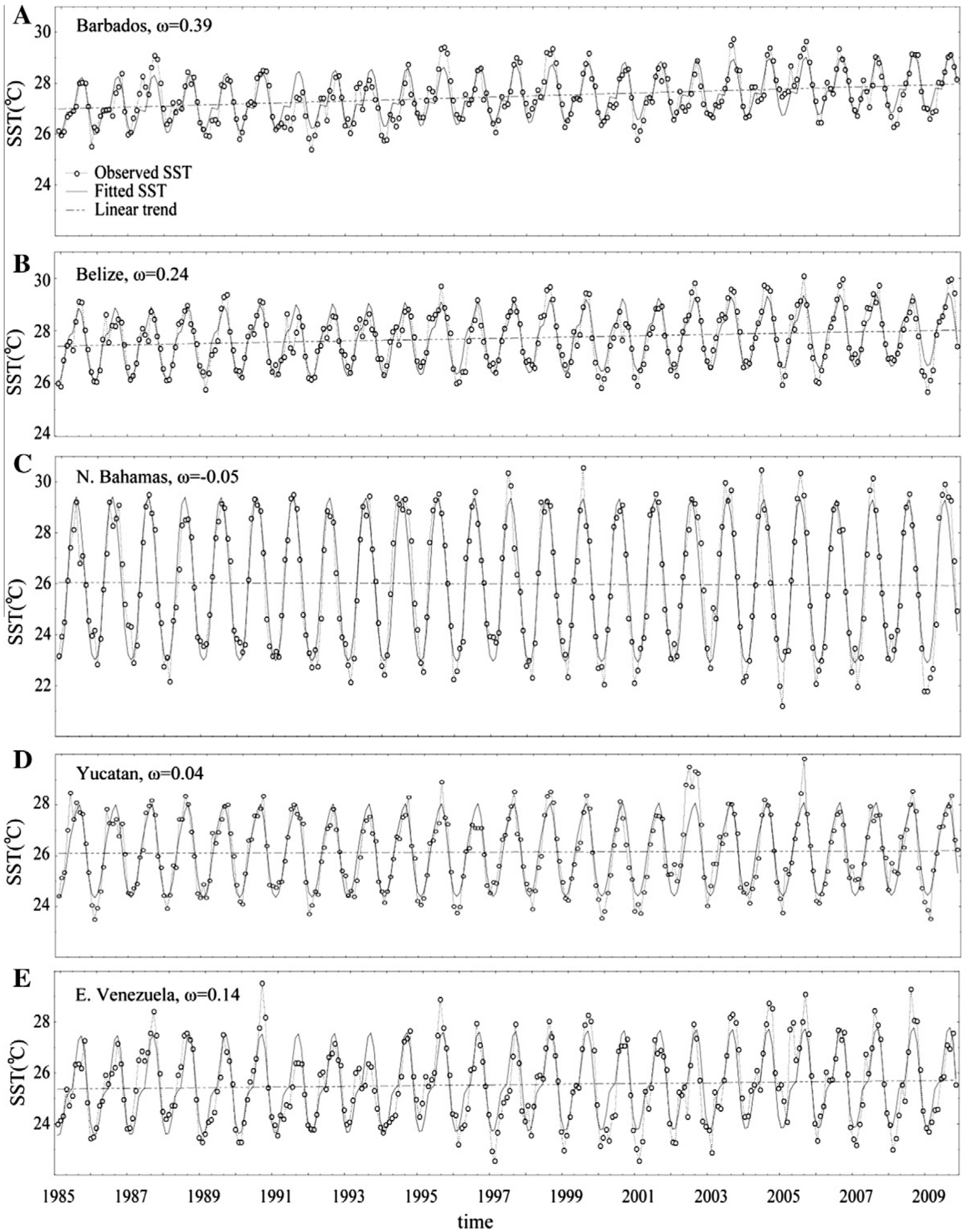

Fig. 2. Observed monthly SST (open circles), model fitting (solid line) and linear trend (ω) in °C decade^{-1}(dashed line) in four locations of the wider Caribbean marked with stars in Fig. 1 (A) Barbados (13.12°N, 59.65°W); (B) Belize (18.00°N, 87.50°W); (C) Northern Bahamas (26.65°N, 78.40°W); (D) Yucatan upwelling (21.68°N, 86.98°W); (E) Eastern Venezuelan coastal upwelling (10.44°N, 64.35°W).

carried out in this area to assess the temporal variability of sub-surface temperature trends of this important link between South Atlantic and North Atlantic waters.

There has been some speculation that climate change may lead to intensification of alongshore winds and thus wind-driven upwelling (Bakun, 1990; Bakun et al., 2010). Although many observations sustain this hypothesis (e.g., Demarcq, 2009), the weakening of upwelling in some areas has also been reported (Pérez et al., 2010). Satellite SST data showed no long-term trends in temperatures at any of the temporal scales assessed in the upwelling area on the northern coast of the Yucatan Peninsula (Merino, 1997). This suggests that there has been no overall change in any of the driving forces of upwelling in this region. Non-significant SST trends in the upwelling system of the southern Caribbean (Andrade and Barton, 2005; Astor et al., 2003) show that upwelling is also active in this area. However, the fast warming observed in

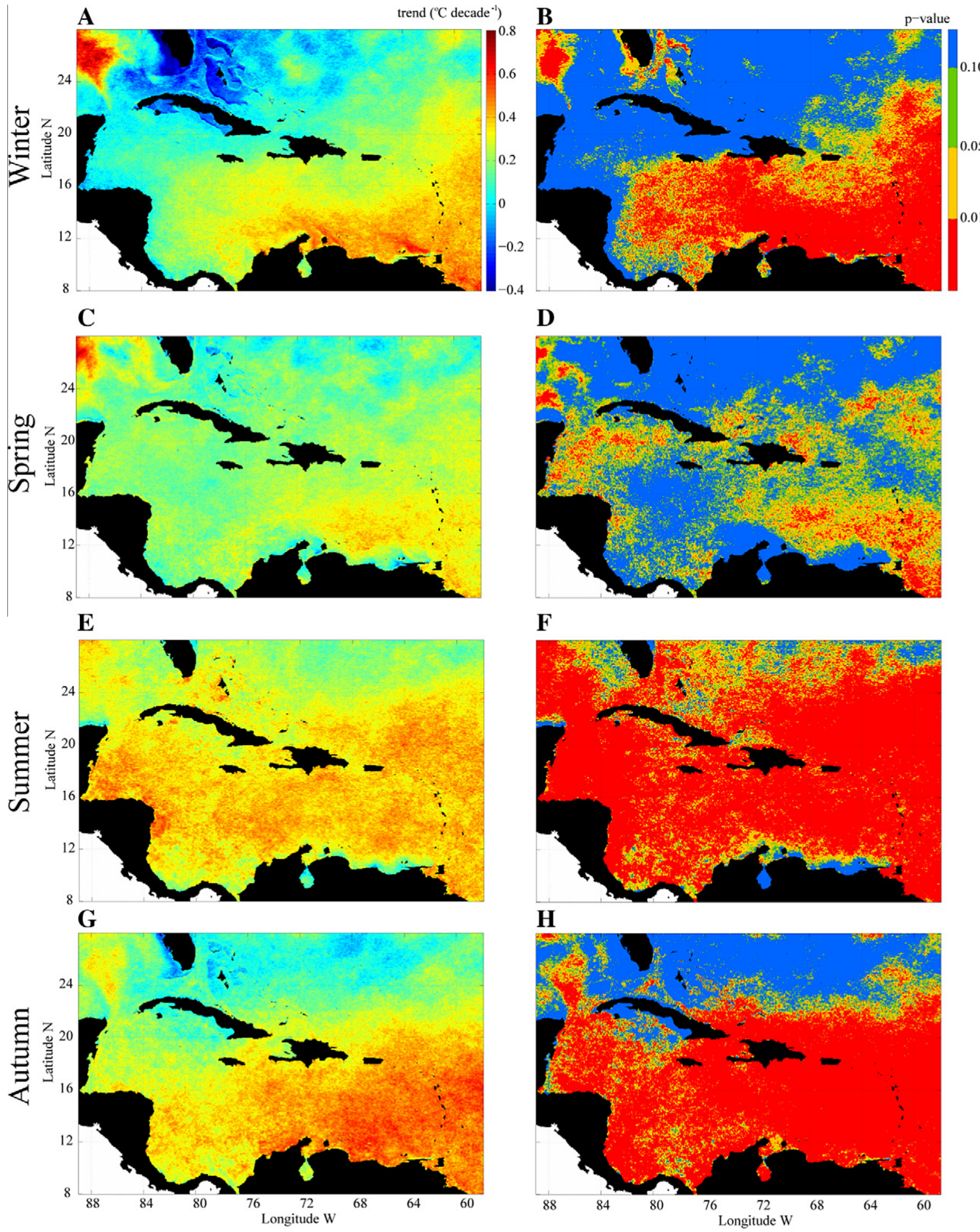

Fig. 3. Seasonal average temperature trends in the Caribbean and associated significance. (A) Winter (December–February) trends; (B) significance of the trend in winter; (C) spring (March–May) trends; (D) significance of the trend in spring; (E) summer (June–August) trends; (F) significance of the trend in summer; (G) autumn (September–October) trends; (H) significance of the trend in autumn.

winter in the area generally influenced by the upwelling plume, suggests that the magnitude of the upwelling is decreasing during its strongest season. The weakening of upwelling could be related to a deepening of the thermocline or to a decrease in the intensity of the winds (Di Lorenzo et al., 2005; Pérez et al., 2010). Temperature observations collected *in situ* in this upwelling area as part of the CARIACO Ocean Time Series Program since 1995 (Müller-Karger et al., 2010) similarly show an increase in winter SST, related to a weakening of the strength of the winds observed between 2003 and at least 2011. These *in situ* observations suggest

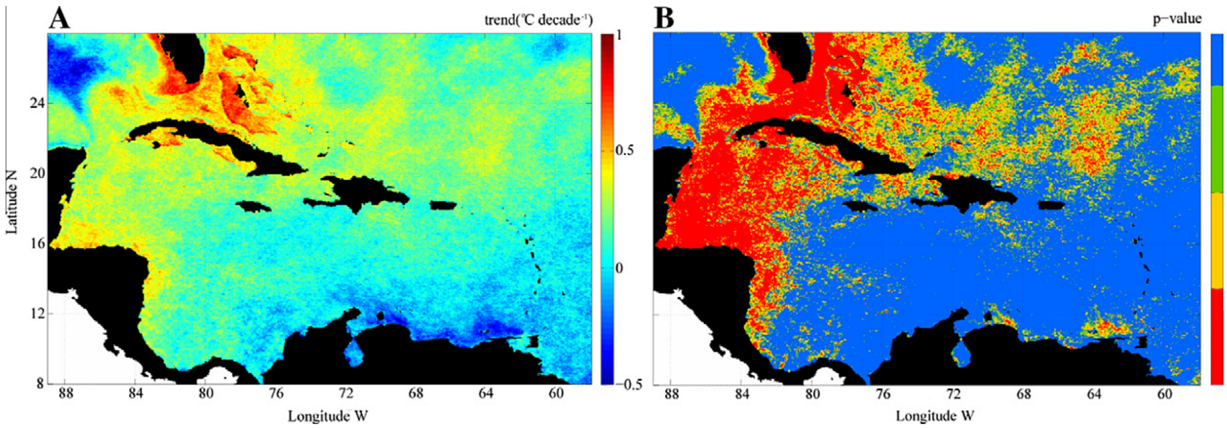

Fig. 4. (A) Trends in annual ranges of temperature (summer–winter); (B) significance of the trend.

that a decrease in the winds may be the cause of the weakening of upwelling in the main upwelling season. On the other hand, the lack of warming of both the upwelling foci and the area influenced by the upwelling plume in summer suggest that the secondary upwelling event (Astor et al., 2003) is still active in this area. The lack of marked warming in the upwelling areas of the Caribbean and the southeast Gulf of Mexico does not imply that ecosystems that depend on the upwelling process will be unaffected by climate change (Mote and Mantua, 2002). Although chronic stress due to long-term temperature increases may not be a major threat for these ecosystems in the near future, acute (short-term) thermal stress events due to higher variability in temperature may influence the dynamics of marine systems (Mumby et al., 2011), and constitute a stress factor also in upwelling areas, despite generally colder temperatures (Chollett et al., 2010).

4.2. Restrictions of the analyses

Clearly, non-significant results shown here should be interpreted with caution. The number of years of data needed to detect a trend depends on the magnitude of the trend as well as the magnitude and autocorrelation of the noise (Weatherhead et al., 1998: Eq. (5)). The AVHRR Pathfinder dataset is the longest available to conduct detailed regional analyses. Yet is still insufficient to provide enough statistical power to assess decadal changes in temperature, especially where changes are small and/or the variability and memory of the SST patterns are high. For these cases, over 40 years of data may be needed to detect significant trends, such as perhaps in the upwelling areas of the southern Caribbean Sea and shelf waters off Florida, the Bahamas and Cuba (Fig. 5). Temporal autocorrelation and internal variability are intrinsic features of each location. Understanding these fundamental characteristics in SST patterns will help in determining reasonable expectations for trend detectability and aid in selecting better sites for climate studies, where the early detection of trends is more likely (Karoly and Wu, 2005; Weatherhead et al., 1998), and for ecological studies, where the trend signal is stronger.

The analyses presented here represent the first detailed portrait of recent changes in SST for the wider Caribbean. However, the dataset and the analyses carried out have three potential limitations which we consider below: (1) biases in satellite temperature data; (2) length of the time series; and (3) omission of the effects of climatic oscillations in the regression analysis. Many factors can affect satellite accuracy when carrying out synoptic studies, including instrument bias (Reynolds, 1993), instrument problems (Zhang et al., 2006), clouds (Kilpatrick et al., 2001) and atmospheric aerosols (Reynolds, 1993). The Pathfinder project has made large efforts in minimizing biases and inconsistencies across the series of AVHRR instruments taking into account the lifetime of the instrument, the occurrence of rare events that could increase interannual variability (such as volcanic eruptions) and seasonal biases (Kilpatrick et al., 2001; Casey et al., 2010). The consistency of SST trends detected with different sources of satellite data (Good et al., 2007; Lawrence et al., 2004; Strong et al., 2008) suggests that temperature trends detected with satellites represent real patterns in recent ocean climate. The Pathfinder algorithm does not consider, however, the influence of spatial biases related to local seasonal weather phenomena, such as desert dust aerosols or cloud coverage that could affect the resulting SSTs (Zhang et al. 2004).Although these factors could contribute to the variability in SSTs and therefore decrease the level of confidence of the trend estimates, there is no evidence of decadal trends in total cloudiness or atmospheric aerosols in the Caribbean basin that could affect the overall patterns presented here.

Our analyses only examine 25 years of data and recent trends in temperature. On one hand, caution needs to be exercised when inferring long-term trends from relatively short records (Allen et al., 1994). However, the increased rate of warming reported during the last 30 years (Trenberth et al., 2007) suggests that the detection of trends in short, but recent datasets is reasonable. Furthermore, physiological and phenological responses of marine organisms are associated to this timescale, granting relevance to the study of recent changes in thermal patterns at detailed temporal and spatial scales.

The regression model used here does not incorporate the effects of climatic oscillations such as El Niño Southern Oscillation, the North Atlantic Oscillation (Czaja et al., 2002; Giannini et al., 2001a) and the Atlantic Multidecadal Oscillation (Knight et al., 2006) that are known to influence temperature patterns in the basin. However, their influence in sea surface temperatures occurs with some delay (Enfield and Mayer, 1997; Giannini et al., 2001b) and the SST response is nonlinear (Hoerling et al., 1997) which makes their inclusion in spatially-explicit predictive models problematic.

4.3. Conclusions

The SST patterns observed in the Caribbean Sea and southeast Gulf of Mexico highlight the importance of regional assessments for determining the rate and timing of warming in particular locations, and the need for caution in extrapolating regional implications from global patterns. The regional changes in SST

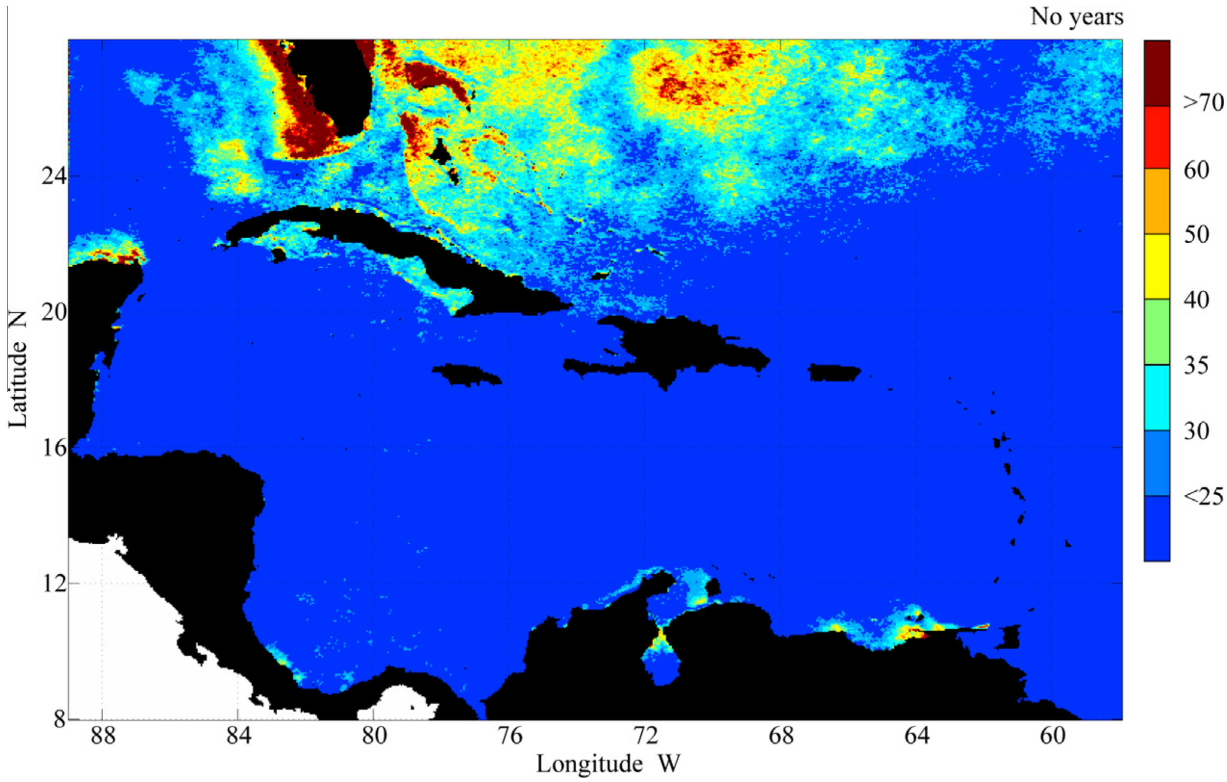

Fig. 5. Number of years required to be able to detect the decadal linear trends described in Fig. 1 A at 95% confidence level (Eq. (5)). Note this study used time series of 25 year length.

trends showed here have not been documented previously. While we still need to understand the ocean processes driving the spatial heterogeneity in temperature trends, it is certain that these patterns are having and will have significant consequences for marine organisms in the region. Although predicting the response of marine ecosystems to warming is difficult, data on SST trends are an important first step. Combined with information on the thermal regime experienced at the location and the thermal performance for the process under study, the temperature patterns presented here would allow testing hypotheses of changes in biological systems using comprehensive ecological datasets. In this regard, more detailed information on the physiological and phenological responses of marine populations of the wider Caribbean to changes in temperature is urgently required as a baseline against which to test the effects of climate change (Baird et al., 2009). The ability of ecosystems to survive these changes in temperatures will depend on migration (e.g., Beaugrand et al., 2002) or adaptation potential (e.g., Császár et al., 2010), as well as the potential to undergo some re-assembly (e.g., Yakob and Mumby, 2011).

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