Gulf of Mexico Science

Volume 23
Number 2 *Number 2*

Article 2

2005

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DOI: 10.18785/goms.2302.02

Gulf of Mexico Science, 2005(2), pp. 161–171

Variability of the Sea Surface Temperature Around Cuba

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Space and time variability of sea surface temperature in oceanic and shelf waters of Cuba were examined using the Advanced Very High Resolution Radiometer (AVHRR) sensors flown on satellites operated by the National Oceanic and Atmospheric Administration from February 1995 to August 2001. Statistics at 90 specific time series stations around Cuba were extracted from the AVHRR images to characterize shelf and oceanic waters using the long-term overall mean, minimum, and maximum sea surface temperature (SST) values. Shelf and oceanic waters reached SST maxima (29.5–30.5°C) in August. Waters off southern and western Cuba reached slightly higher temperatures than those off the northeast in the Old Bahamas Channel; waters along the northern coast of Cuba were about 1°C cooler on average than those along the southern coast. Oceanic waters around Cuba experienced minima (24.5–25.5°C) in February–March, about a month after shelf waters. Only minor regional differences in maximum temperatures were observed in shelf areas. Shelf regions around Cuba have lower annual average SSTs than adjacent oceanic waters, and the range of monthly average SST of shelf waters exceeded that of oceanic waters by 3°C, with the largest differences observed during winter. Shelf waters also cooled down at >0.04°C/d, or twice as fast as oceanic waters (0.02°C/d) by action of sensible heat and evaporative losses. Shelf waters also warmed up at rates exceeding 0.06°C/d, which was two to three times faster than oceanic waters (0.02–0.03°C/d). SST anomalies were slightly positive between February 1995 and February 1999 and slightly negative from October 1999 to August 2001. In summer of 1995, 1997, and 1998, coral bleaching was observed in northern and southern reefs of Cuba. Summer anomalies >1°C occurred in May 1995 and August 1997, which may have contributed to the coral bleaching.

The temperature of the ocean surface plays a key role in determining conditions for survival of organisms that inhabit shallow waters, for ocean-atmosphere exchange processes of energy and gases, and vertical mixing and upwelling processes, and is of general interest to humans for various purposes such as forecasting weather and natural hazards, and even the vitality of industries such as tourism, fishing, and aquaculture. Spatial and temporal patterns of variation of sea surface temperature (SST) therefore reflect conditions that affect a broad range of processes. Measurement of this basic property can help better understand oceanic ecosystems and whether there are secular changes in the marine environment.

Coastal waters of Cuba support significant commercial and subsistence fisheries, coastal population growth, and development largely associated with tourism, but the environment affected by these activities remains largely understudied. Understanding the variability of SST distribution around Cuba is critical to understanding physical and biological oceanographic processes, including metabolism and health of marine organisms in a coastal zone that is undergoing rapid development (Claro et al., 2001). Most of these infrastructure development activities focus on the following four major separate coastal archipelagos (Fig. 1; Table 1; but see also Table 2):

Region 1: Los Canarreos Archipelago, located in southwestern Cuba. This region includes 672 islands, keys, and islets, the biggest of which is Isla de la Juventud (Isle of Youth), and the southwestern shelf of Cuba defined by the Gulf of Batabanó.

Region 2: Jardines de la Reina Archipelago, located in southeast Cuba. This region includes 661 keys and islets, and the southeastern shelf of Cuba defined by the Gulf of Ana María and the Gulf of Guacanayabo.

Region 3: Los Colorados Archipelago, located to the northwest of Cuba, with 160 keys and islets; includes the northwestern shelf of Cuba defined by the Gulf of Guanahacabibes.

Region 4: Sabana-Camagüey Archipelago, located in north-central Cuba, also known as

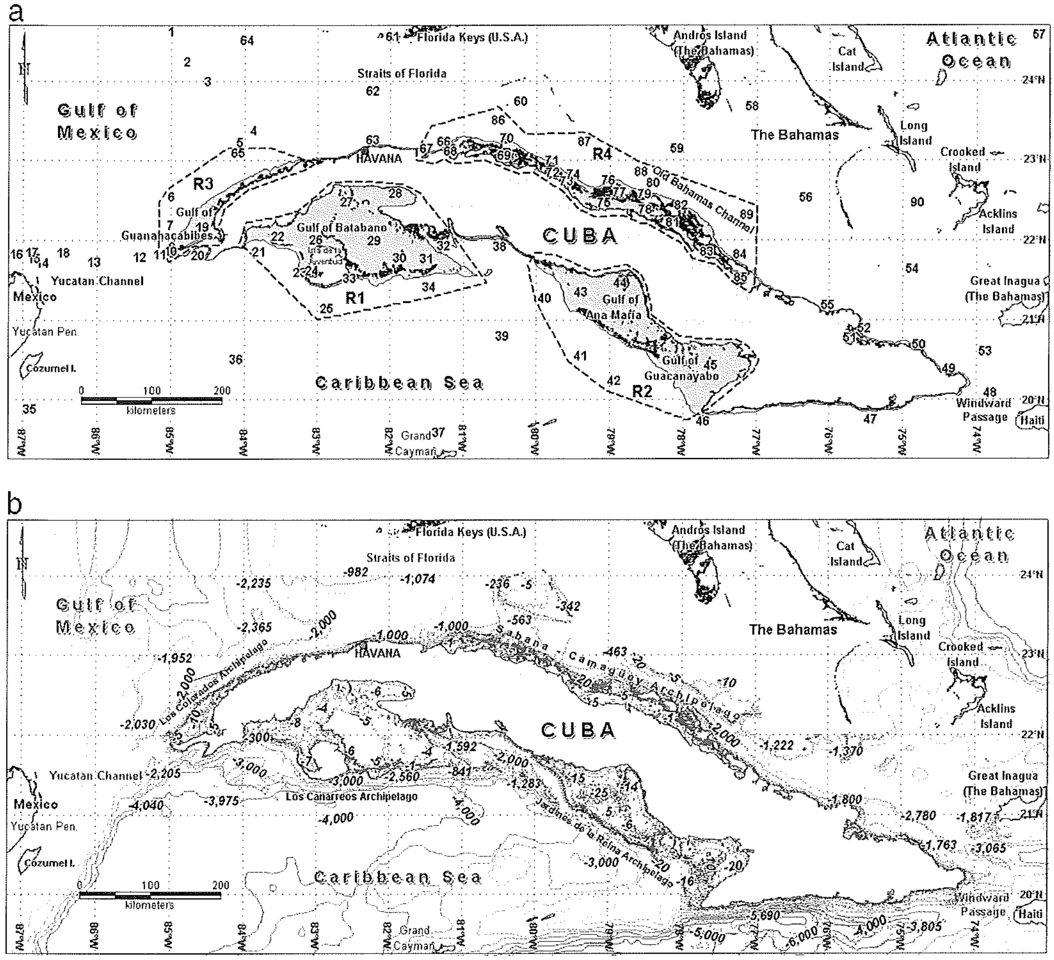

Fig. 1. (a) Study area with the location of 90 stations from which satellite-derived SST time series were extracted. Regions delimited by broken lines (R1, R2, R3, and R4) represent the four major Cuban archipelagos (Table 1). (b) Bathymetry around Cuba (meters).

Jardines del Rey. This region consists of 2,517 islands, keys and islets; it includes the north-central shelf of Cuba and several large bays.

Sverdrup et al. (1942) found that average SSTs in the western Caribbean Sea south of Cuba ranged from 25.0°C in January–February to about 28.0°C in August. Subsequently, other studies observed that southern Cuba shelf waters exhibited a much wider range, with a maximum of 33.0°C during summer in shallow waters of the northwestern sector of the Gulf of Batabanó, and a minimum of 22.0°C in the Gulf of Ana María in winter (Duarte Bello, 1958; Suarez-Caabro, 1959; Suarez-Caabro and Duarte Bello, 1962; Emilsson and Tapanes, 1971). Lluis Riera (1977) also observed values of 24.0°C and 29.9°C for February and August, respectively, in the Gulf of Ana María and Gulf of Guacanayabo.

Using reversible thermometers, Blázquez (1981) studied the seasonal variability of SST off northwestern Cuba in 1964 and 1965 and found little difference in the summer SST maxima between coastal, shelf, and offshore waters. However, during winter, he observed that lower SST occurred over the shelf compared to nearby oceanic regions.

García (1981) published a comprehensive study of regional SST patterns using data from eight different cruises conducted between 1966 and 1980 and data published by Robinson (1975). García concluded that the SSTs off the southern coasts of Cuba were warmer than those of the northern coasts by approximately

TABLE 1. Location of 50 stations sampled around Cuba, grouped by region.

Regions	Description	Station no.
R1	S of Los Canarreos Archipelago and Gulf of Batabanó (southwest Cuba): oceanic waters	21, 23, 25, 32, 33, and 34
	The southwestern insular shelf of Cuba defined by the Gulf of Batabanó: shelf waters	22, 24, 26, 27, 28, 29, 30, and 31
R2	S of Jardines de la Reina Archipelago and Gulf of Ana María (southeast Cuba): oceanic waters	40, 41, and 42
	The southeastern insular shelf of Cuba defined by the Gulf of Ana María and the Gulf of Guacanayabo: shelf waters	43, 44, and 45
R3	W Los Colorados Archipelago (northwest Cuba): oceanic waters	6, 7, 8, 9, 10, and 65
	The northwestern insular shelf of Cuba defined by the Gulf of Guanahacabibes: shelf waters	19
R4	N of Sabana–Camagüey Archipelago (northcentral Cuba): oceanic waters	66, 67, 70, 71, 74, 76, 79, 80, 82, 84, 86, 87, 88, and 89
	The northcentral insular shelf of Cuba defined by several bays: inner shelf waters	68, 69, 72, 73, 75, 77, 78, 81, 83, and 85

1°C on a year-round basis, except for a period around July, when similar maxima occurred everywhere around the island. Minima were observed during January–February.

Despite the efforts of these studies, the collection of basic oceanographic data around the island of Cuba has been sparse and irregular. Different studies have focused on different locations, and the lack of common standards and variation in data quality may have contributed to differences in SSTs reported by different authors. Indeed, the limited amount of data has precluded any systematic study of change in environmental conditions around the island over both short (within-year) and long (interannual to decadal) periods. To date, there has been no detailed, coherent, and comprehensive assessment of SST variability around Cuba.

The availability of reliable, synoptic, and high-spatial-resolution SST observations from space-based sensors since the mid-1980s provides a unique opportunity to examine the var-

TABLE 2. Location of stations sampled outside Regions 1–4 (Table 1).

Zones (oceanic or shelf waters)	Station no.
North of Havana: oceanic waters	63
Straits of Florida: oceanic waters	62
Key West (Florida Keys): shelf waters	61
Cay Sal Bank (The Bahamas): shelf waters	60
South of Cienfuegos (Cuba): oceanic waters	38 and 39
The southeastern area of Cuba: oceanic waters	46 and 47
The northeastern area of Cuba: oceanic waters	49, 50, 52, 53, 54, and 55
Winward Passage: oceanic waters	48
Corrientes Bay: oceanic waters	20
Nipe Bay: shelf waters	51
Yucatan Channel: oceanic waters	11, 12, 13, and 18
Bank of Bahamas: shelf waters	56, 58, 59, and 90
NE of the Peninsula of Yucatan: shelf waters	14, 15, 16, and 17
Gulf of Mexico: oceanic waters	1, 2, 3, 4, 5, and 64
NW of Caribbean Sea: oceanic waters	36 and 37
South of Cozumel Island: oceanic waters	35
Atlantic Ocean: oceanic waters	57

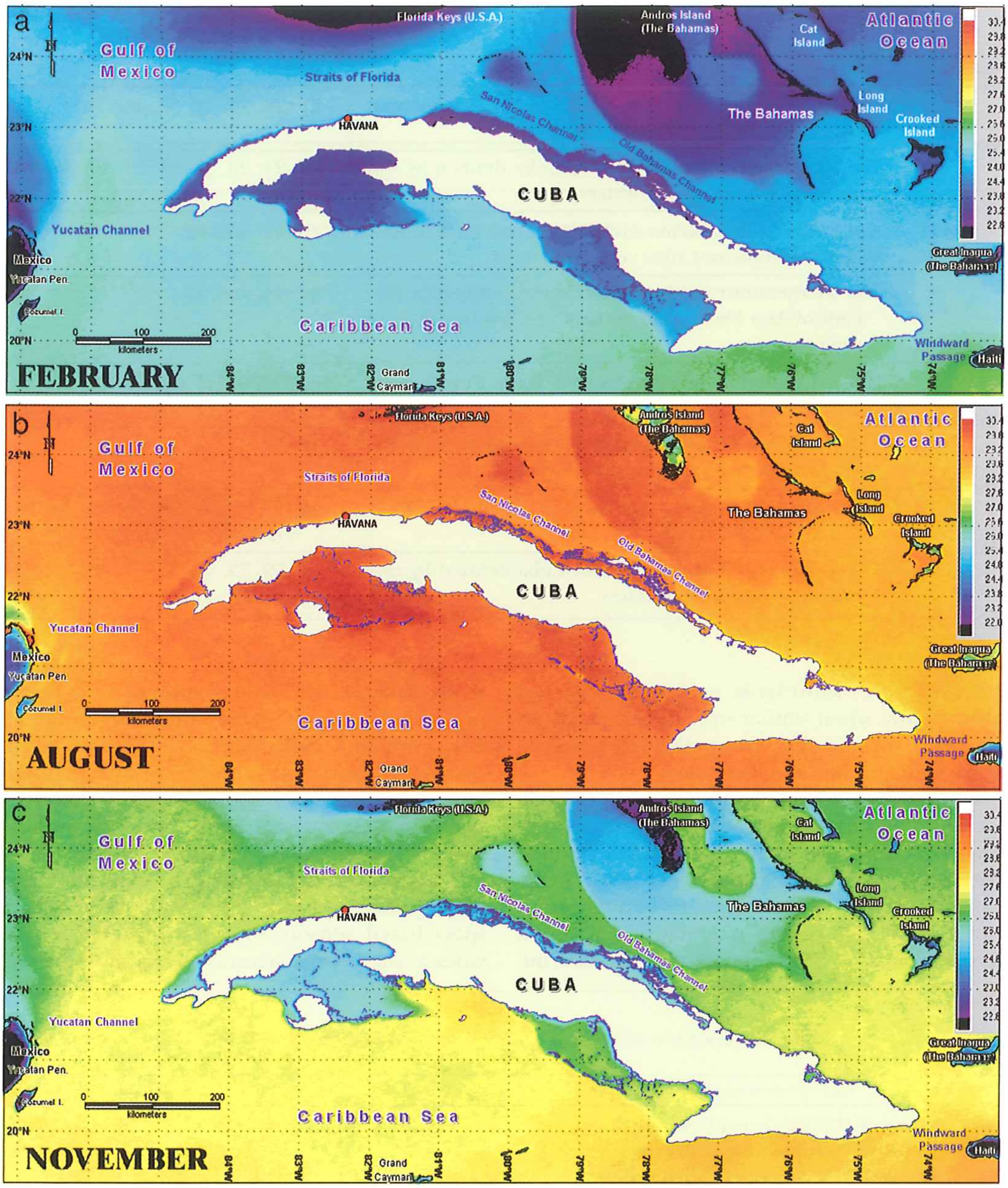

Fig. 2. Climatological AVHRR-SST fields (1995 to 2001): (a) February, (b) August, and (c) November.

iability of this basic environmental parameter around the island of Cuba. Studies focusing on other regions have used such data to understand phenomena such as El-Niño Southern Oscillation (ENSO), the effect of eddy turbulence and other environmental variability on biological patchiness (Mete Uz and Yoder, 2004), and the potential of stress on coral reef communities due to ocean warming (Gleeson and Strong, 1995). Here we use an extensive SST time series of satellite images to describe, for the first time, the most basic patterns in SST variability in shelf and oceanic waters around Cuba (see Figure 2).

Methods

Time series of SST were derived from the Advanced Very High Resolution Radiometer (AVHRR) sensors flown on the NOAA-12 and NOAA-14 satellites operated by the National Oceanic and Atmospheric Administration

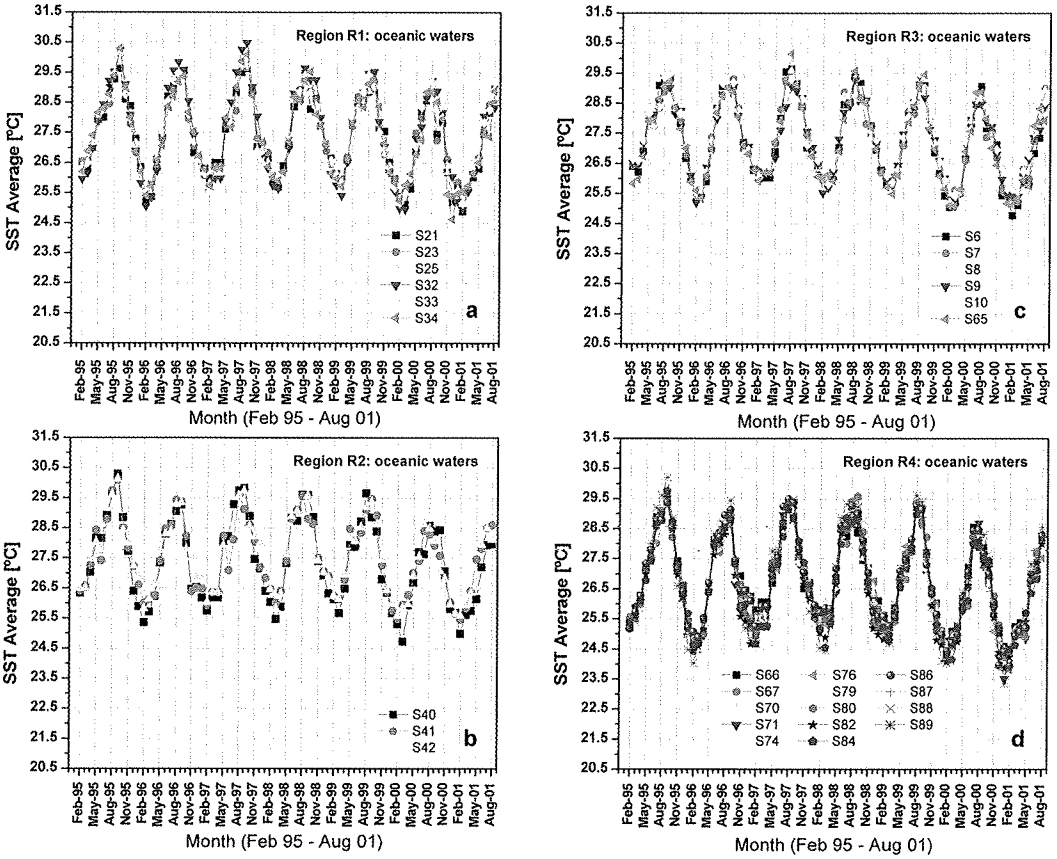

Fig. 3. Time series (February, 1995–August, 2001) of monthly mean AVHRR-SST in oceanic waters of Regions (a) 1, (b) 2, (c) 3, and (d) 4.

(NOAA), using images captured with a ground-based antenna located at the University of South Florida (St. Petersburg, FL), from February 1995 to August 2001. A total of 14,291 daily images were examined.

The AVHRR images were used to measure SST in the western Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico with a spatial grid resolution of 1.1 km. SSTs were derived using the Multi-Channel Sea Surface Temperature split window techniques (McClain et al., 1983; Strong and McClain, 1984; Walton, 1988). The nominal accuracy of AVHRR-SST retrievals is in the range of ±0.3 to ±1.0°C (see also Brown et al., 1985; Minnett, 1991). Images were mapped to a window corresponding to 19.2°N–24.7°N and 73.0°W–87.2°W (image size was 1,576 × 610 pixels; pixel size was 1.1 km × 1.1 km).

Time series were extracted from the satellite images at 90 stations (each represented by a 3 × 3 pixel sample) located over the shelf and in oceanic waters around Cuba (Fig. 1; Tables 1, 2). Most station locations were chosen at random, whereas some coincided with historical studies. Each time series was filtered by comparing the original series with a smoothed 40-day running mean and eliminating individual values that exceeded a difference of $\Delta T = 1°C$ from the running mean. This helped eliminate cloud-contaminated data, which generate colder than usual pixels. Composite images were also derived by averaging series of images over sequential 7-d periods, as well as over monthly and annual periods. Finally, a series of 12 monthly SST climatologies were derived by averaging all data from each month across all available years (Fig. 2). Monthly SST anomalies were computed by subtracting individual monthly means from these climatological means.

Results and Discussion

Time and space SST variability.—Stations within each of the four regions around Cuba showed

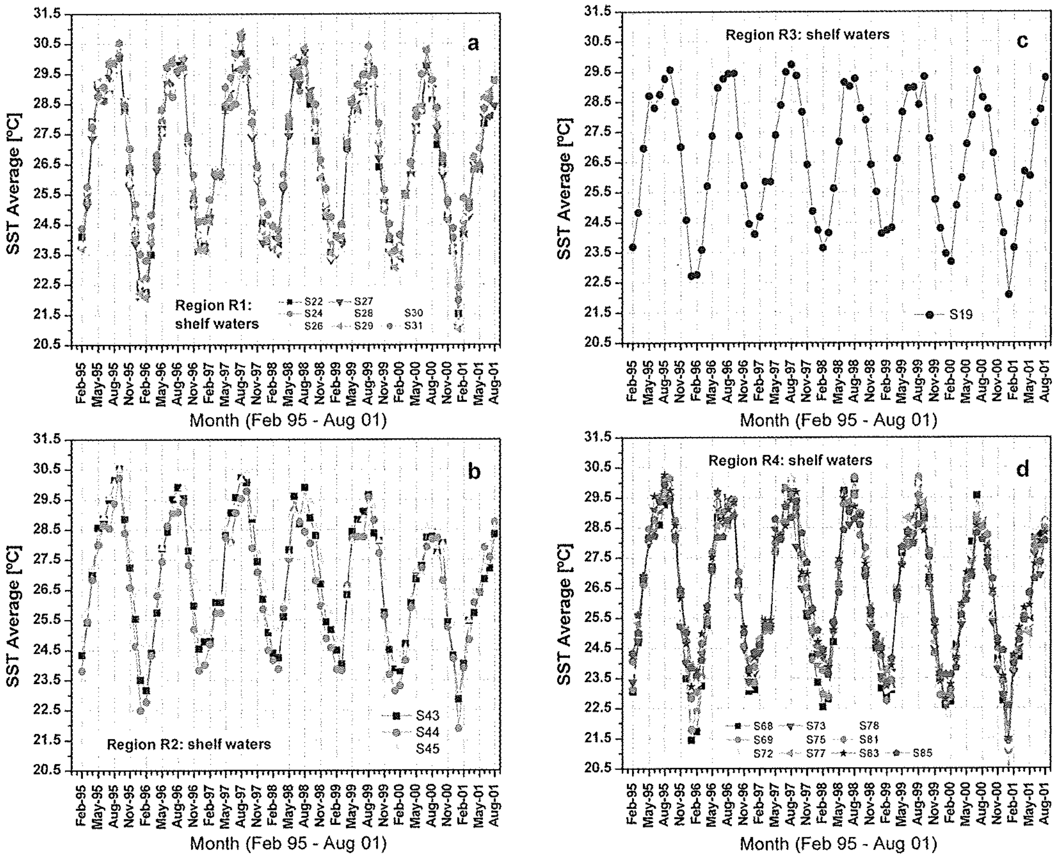

Fig. 4. Time series (February, 1995–August, 2001) of monthly mean AVHRR-SST in shelf waters of Regions (a) 1, (b) 2, (c) 3, and (d) 4.

similar temperature variability, but there were differences between the regions (Fig. 2a–c). Waters along the northern coast of Cuba were on average about 1°C cooler than along the southern coast (Fig. 2), confirming the observations of Garcia (1981). The climatological images (Fig. 2) show the warm influence of central Caribbean waters southeast of Cuba on a year-round basis. The images show that the Old Bahamas Channel tends to be cooler than waters west and south of Cuba.

SSTs were particularly uniform around the island during summer, with only small SST differences visible between shelf and oceanic waters (Fig. 2b). SST maxima occurred at about the same time in all regions; namely, between July and September but most typically in August (about 29.5–30.5°C; Figs. 3, 4). Waters off southern and western Cuba reached slightly higher temperatures than those off the northeastern end of the island in the Old Bahamas Channel.

Shelf waters showed a range of monthly average SST that exceeded by 3°C the range observed over deep waters. The largest differences between shelf and oceanic waters were observed during winter. All shelf regions around Cuba had lower annual average SSTs than adjacent oceanic waters (Figs. 2–4). The highest overall average SST values occurred in Region 1, in the southwestern shelf of Cuba defined by the Gulf of Batabanó (Station 30: 31.91°C). Region 2 also showed higher summer SST values (maximum at Station 45: 31.64°C), compared to stations of northern Cuba. Oceanic waters experienced minima of 24.5–25.5°C in February–March, about a month after shelf waters. Regional seasonal (~23°C) and interannual (21.5°C) SST minima occurred in inner shelf waters off northern Cuba in Region 4. Overall SST minima were registered in shelf waters of Region 4 between December and February but most typically in February (the lowest SST occurred at Station 73: 18.76°C in coastal lagoon waters within Region 4).

Shelf regions cooled down faster than oce-

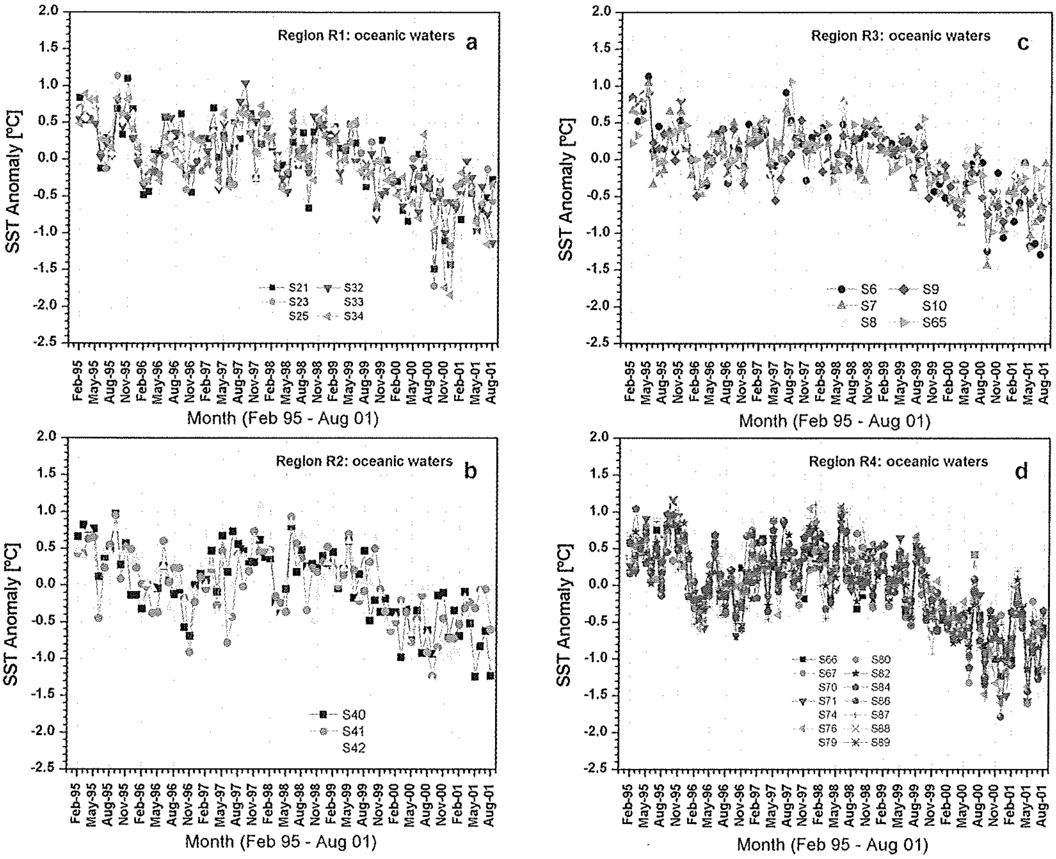

Fig. 5. Time series (February, 1995–August, 2001) of monthly anomalies of AVHRR-SST in oceanic waters of Regions (a) 1, (b) 2, (c) 3, and (d) 4.

anic waters, by action of sensible heat and evaporative losses (Warrior et al., 2002). This causes rapid mixing to the bottom over shallow areas, thus cooling the entire water column. Indeed, the satellite data show that shelf regions around Cuba cooled down at a rate >0.04°C/d, from maxima in August to minima of 22.5–23.5°C in January–February. This was twice the cooling rate of adjacent oceanic waters (0.02°C/d).

Shelf waters also warmed up at rates >0.06°C/d, which was two to three times faster than warming of oceanic waters (0.02–0.03°C/d). This rapid heating rate over the shelf is likely in part due to the reflection of light from the bottom in shallow areas, thus providing for significant additional radiation input to the water column relative to deep waters, where photons are absorbed over deeper paths (Warrior et al., 2002).

SST anomalies.—To study the interannual variability of SST around Cuba, we examined SST anomalies that had the seasonal cycle removed. The anomaly was defined as the difference between the monthly average SST and the monthly climatological SST for each month between February 1995 and August 2001. The analysis was carried out at each station (Tables 1, 2). To illustrate the most important interannual changes, we selected four groups of stations in oceanic waters in each of the four regions and similarly within each of the shelf areas.

There was a very good correlation in SST anomalies between stations within each group, both in shelf or oceanic region (Figs. 5, 6). Over shelf areas, February seemed to be the month with the largest fluctuations in temperature anomalies, from a colder than normal year followed by a warmer than normal year spanning a range in interannual differences of almost 3°C. Further, anomalies in shelf waters seemed to have a periodicity of between 6–8 mo. Visual inspection of Figures 5 and 6 suggests that, in very general terms, oceanic waters

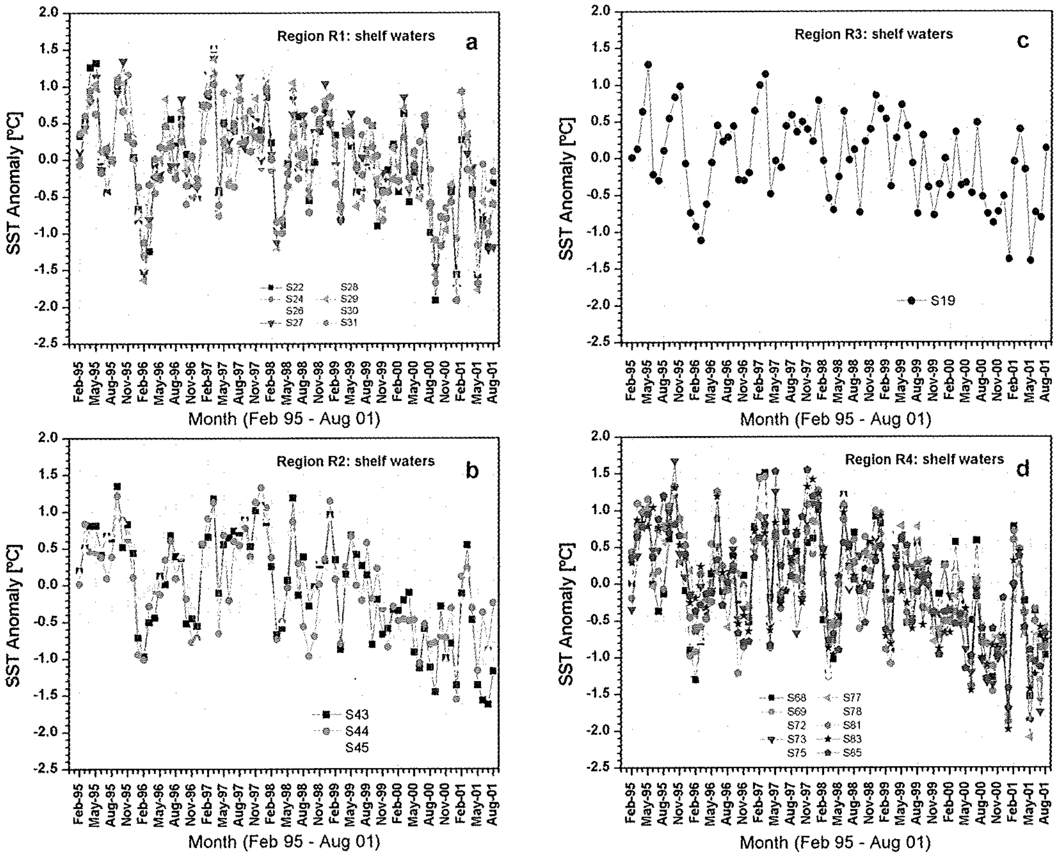

Fig. 6. Time series (February, 1995–August, 2001) of monthly anomalies of AVHRR-SST in shelf waters of Regions (a) 1, (b) 2, (c) 3, and (d) 4.

showed similar temporal variation in the SST anomalies as the shelf stations contained within the same region, but with much more muted amplitude (the range of oceanic variation was about half of concurrent variations on the shelf). The patterns of the entire ensemble of time series (Fig. 7) suggested that, except for the exceptionally cold anomalies (−1.5°C) of February 1996 over continental shelves around Cuba, both oceanic and shelf areas showed on average slightly positive SST anomalies between February 1995 and February 1999 relative to the period October 1999–August 2001, over which slightly cooler anomalies dominated.

The problem of coral bleaching has gained significant attention as an apparent result of prolonged warm periods (Gleeson and Strong, 1995). However, coral reefs seem to be particularly stressed when they experience a very warm period after a colder than normal period (Hoegh-Guldberg and Smith, 1989). Indeed, coral bleaching may occur when these organisms have been stressed during exceptionally cold winters and then experience 1–2 d exposures to temperatures +3–4°C above the normal maximum, or after several weeks of exposure to anomalies of +1–2°C (Coles et al., 1976; Wilkinson et al. 1999; NOAA, 2004). Bleaching due to warm thermal stress was documented in Cuban coral reefs by Alcolado et al. (2003) in summers of 1995, 1997, and 1998. The AVHRR SST data showed that summer anomalies >+1°C relative to the long-term mean occurred in August–October 1995 and in most of 1997 throughout the region both on and off the shelf (Fig. 7). Indeed, there was a large coral bleaching event in Cuba in August 1997 (SST >~30°). In 1998, there was a large change from cooler than normal temperatures in March to warmer than normal in June and July, with yet another cool anomaly in September. During 2000 and 2001, relatively strong negative anomalies (larger than −0.5°C) were observed during winter throughout the region. Overall, the anomalies suggest

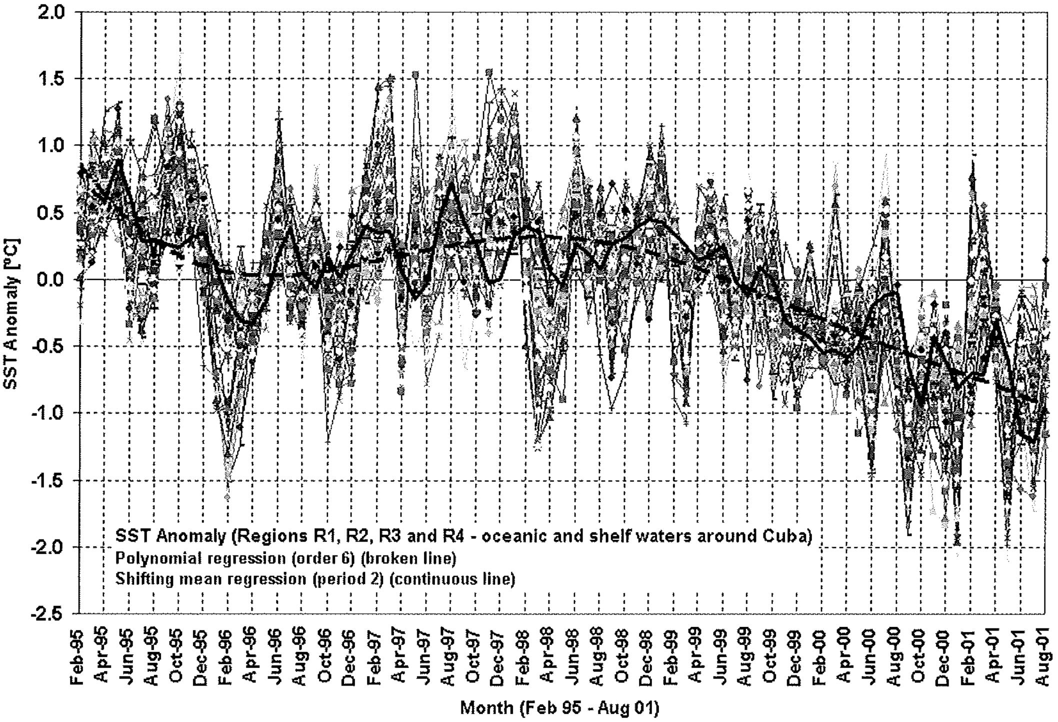

Fig. 7. Combined time series of SST anomalies for shelf and oceanic waters around Cuba. Polynomial regression of order 6 is shown as a broken line, with a running mean regression (period 2) as a heavy continuous line.

that the entire area cooled about 1°C over the 6-yr period studied.

Previous analyses have suggested that meteorological conditions in the Caribbean are linked to ENSO events (Enfield and Mayer, 1997; Giannini et al., 2000; Melo Gonzalez et al., 2000; Giannini and Kushnir, 2001; Hoerling et al., 2002). The AVHRR record available for this study is too short to examine possible relationships between SST and ENSO in any robust manner. We found no statistical relationship between SST and either ENSO or the North Atlantic Oscillation (NAO), even after considering possible lag times of up to 6 mo. The mechanisms that would lead to meteorological connections with ENSO identified by previous studies, and particularly the impacts on oceanographic processes are, indeed, not clear yet.

Conclusions

Cuban waters show a seasonal SST amplitude of about 7–9°C between the lowest average SST in shelf waters off north-central Cuba and the highest average SST off southwestern Cuba. Waters along the northern coast of the island showed SSTs nearly 1°C lower than along the southern coast. Temperature along the northern coast decreased from west to east, independently of the season, showing the warming influence of the Caribbean waters as they flow toward the Gulf of Mexico. Shelf regions around Cuba showed lower annual average SSTs than oceanic waters. While shelf waters reached SST maxima similar to those of adjacent oceanic waters in summer (about 29.5–30.5°C in August), shelf waters cooled down almost twice as fast (0.04°C/d) and were colder in winter (22.5–23.5°C in January–February) than oceanic waters (24.5–25.5°C in February–March). Shelf waters also warmed up at rates >0.06°C/d, or almost three times faster than oceanic waters (0.02–0.03°C/d).

Some evidence was found of strong positive SST anomalies (>1.0°C) during summer in 1995, 1997, and 1998, but it was not apparent that they were sustained for longer than a month except in 1997. During 2000 and 2001, relatively strong negative anomalies (larger than −0.5°C) were observed during winter throughout the region. This led to an overall trend of decreasing temperatures over the 6-yr study, with an overall decrease of order of 1°C between 1995 and 2001. No significant relationship was observed between SST or SST anomalies and ENSO or NAO indexes.

ACKNOWLEDGMENTS

We thank Mario Villaverde of the Instituto de Oceanología of Cuba for his help in the development of software used for data processing. We also thank Ranulfo Rodriguez from the Instituto de Ciencias del Mar y Limnología, UNAM-Mexico, for his expert advice on satellite data processing. Dr. Nan Walker of Louisiana State University and two anonymous reviewers provided comments that improved this manuscript significantly. Funding to participate in this study was provided in part (to FMK) by the National Aeronautics and Space Administration.

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