Hydrobiologia
DOI 10.1007/s10750-008-9440-y

PRIMARY RESEARCH PAPER

The impact of the 1997–1999 warm-SST and low-productivity episode on fisheries in the southwestern Gulf of Mexico

M. Manzano-Sarabia · C. A. Salinas-Zavala · M. Kahru · S. E. Lluch-Cota · A. González-Becerril

Received: 16 January 2008 / Revised: 17 April 2008 / Accepted: 21 May 2008

Abstract Satellite-derived time-series of sea surface temperature (SST), chlorophyll *a*, and net primary productivity showed a period of warm SST and low productivity during 1997 and 1999 in the southwestern Gulf of Mexico followed by a period of colder than average SST (2000–2001). This shift between the warm and cold oceanic conditions might have caused significant changes in the structure of the ecosystem that is shown by changes in primary productivity and fishery landings between those periods.

Keywords Sea surface temperature · Chlorophyll *a* · Primary productivity · Fisheries

Handling editor: L. Naselli-Flores

M. Manzano-Sarabia (✉) · C. A. Salinas-Zavala · S. E. Lluch-Cota
Centro de Investigaciones Biologicas del Noroeste, S.C. (CIBNOR), P.O. Box 128, La Paz, Baja California Sur, Mexico
e-mail: marlenne04@cibnor.mx

C. A. Salinas-Zavala
e-mail: csalinas@cibnor.mx

M. Kahru
Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92093-0218, USA

A. González-Becerril
Centro Regional de Investigacion Pesquera, Instituto Nacional de la Pesca., Manzanillo, Colima, Mexico

Abbreviations

Chl-a	Chlorophyll *a*
ENSO	El Niño Southern-Oscillation
IAS	Intra-Americas Sea
NPP	Net primary productivity
PCA	Principal component analysis
PC1	First principal component
SLA	Sea level anomaly
SST	Sea surface temperature
SWGM	The southwestern Gulf of Mexico
WHWP	Western Hemisphere Warm Pool

Introduction

The southwestern Gulf of Mexico (SWGM) has been recognized for its energetic resources and high biotic potential (Vidal-Hernández & Pauly, 2004). Fluctuations in the distribution, abundance, recruitment, availability of marine fish populations, trophic interactions, and energy fluxes have been studied by several authors, most of them focusing on overfishing-related changes and mass-balanced ecosystem models (Arreguín-Sánchez & Manickchand-Heileman, 1998; Arreguín-Sánchez et al., 2004; Burgos & Defeo, 2004; Ramírez-Rodríguez et al., 2000, 2003). The dynamics for many species still remain unknown in the SWGM so that describing changes in the ocean are also needed as alternative explanations of declining stocks in the SWGM not fully explained by overfishing. Specifically, the structure of ecosystems is associated with changes in ocean temperatures (Bakun & Broad, 2003; Chavez et al., 2003) because this environmental variable influences distribution patterns and growth of phytoplankton and populations of marine fish (Dower et al., 2000). Satellite-derived chlorophyll *a* concentration (Chl-a) is used as a proxy of phytoplankton biomass and to estimate net primary productivity (NPP) throughout the photic zone (Behrenfeld et al., 2006), and those variables are also linked with fluctuations of fishery yields (Nixon,1988) in addition to those caused by fishing pressure. The sea surface temperature (SST), Chl-a, NPP, and fishery yields are strongly influenced by interannual events, such as those caused by the El Niño-Southern Oscillation (ENSO) in the Pacific Ocean, because this phenomenon causes a multitude of changes in oceanic and atmospheric conditions and consequently causes strong effects on marine populations and ecosystems (Chavez et al., 1999; Kahru & Mitchell, 2000). The ENSO effects are also transferred to the Atlantic Ocean by means of a teleconnection, a known atmospheric bridge (Wang & Enfield, 2001, 2003) causing an anomalous warmth in the tropical North Atlantic (TNA) and a large Western Hemisphere warm pool (WHWP). The WHWP is the region defined by an SST warmer than 28.5°C comprising the Eastern North Pacific (ENP), Gulf of Mexico (GM), Caribbean Sea, and the western tropical North Atlantic (TNA). It starts to develop in the ENP during the boreal spring and expands into the GM in summer, then moving south into the Caribbean Sea and expanding into the TNA in late summer and early fall, e.g., Fig. 1 in Wang and Enfield, 2003. Large WHWP events (25% larger than the climatological area according to Wang et al., (2006)) have occurred during the boreal summers following some ENSO events (1958, 1969, 1983, 1987, 1997, and 1998). Although the effects of the large WHWP of 1997–1998 on atmosphere and oceanic conditions have been publicized (Wang & Enfield, 2001, 2003; Wang, 2005; Wang et al., 2006; Enfield et al., 2006), knowledge of their likely impact on the ecosystem structure is scarce. In this paper, we will discuss the interannual variability of satellite-derived SST, Chl-a, and NPP, emphasizing the response during the ENSO-linked large warm pool of 1997–1998, and will also discuss the likely signature on higher trophic levels (using fishery landings as a proxy) in the SWGM.

Data and methods

Forty-six monthly, officially reported commercial landings (Table 1) were compiled for the SWGM during 1997 and 2003 (total catch recorded for Campeche State, Mexico, Fig. 1) and standardized (calculated by subtracting the monthly mean from its monthly observed value, then dividing by the standard deviation). Data were made available by Sub-Delegación de Pesca in Campeche State, Mexico. Catch records, reported as common names, are first recorded at landing locations or gathered by "mediators" and later reported to local fishery officers (see Arreguín-Sánchez and Arcos-Huitrón, 2007). A longer catch-time-series exists, but only for a few species and with an annual resolution, e.g., since 1970 for the red grouper (Giménez-Hurtado et al.,

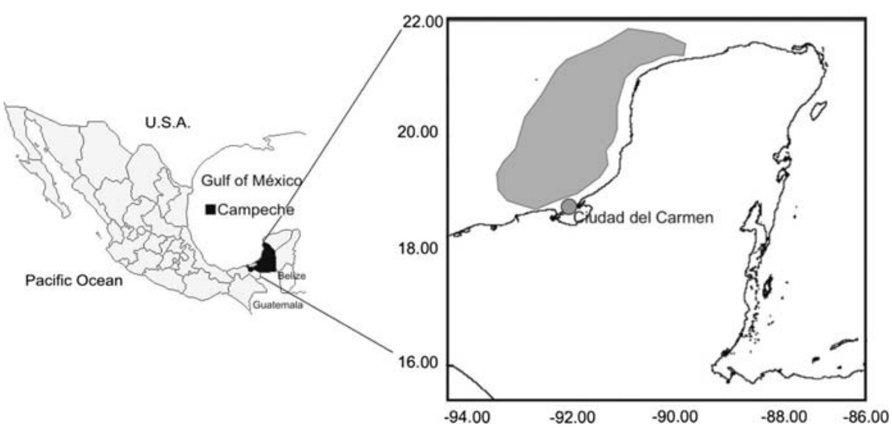

Fig. 1 Study area. Time-series of SST, chlorophyll *a*, and net primary productivity were constructed in the southwestern Gulf of Mexico (dark shaded gray area). Forty-six monthly commercial landings (1997–2003) were compiled from Campeche State (Mexico)

Table 1 Reported fishery landings in Campeche State

Group	Common name	Spanish common name	Family	Factor loadings
Catfishes	Sea catfish	Bagre	Ariidae	−0.39
	Gafftopsail sea catfish	Bandera	Ariidae	0.79
	Dark sea catfish	Bagre prieto	Ariidae	0.47
Pampanos and jacks	Crevalle jack	Jurel	Carangidae	0.33
	Almaco jack	Esmedregal	Carangidae	0.54
	Permit	Palometa	Carangidae	−0.19
	Palometa	Pampano	Carangidae	0.51
	Blue runner	Cojinuda	Carangidae	0.51
	Greater amberjack	Coronado	Carangidae	0.29
Sharks	Shark	Cazón	Carcharhinidae, Sphyrnidae	0.34
Snooks	Fat snook	Chucumite	Centropomidae	0.65
	Common snook	Robalo	Centropomidae	0.83
Mojarra	Mayan cichlid	Mojarra castarrica	Cichlidae	0.43
	Striped mojarra	Mojarra blanca	Gerreidae	−0.17
Grunts	Grunt	Chacchi	Haemulidae	−0.04
	Pigfish	Armado	Haemulidae	−0.15
Squids	Squid	Calamar	Loliginidae	−0.12
Snappers	Red snapper	Huachinango	Lutjanidae	0.88
	Lane snapper	Villajaiba	Lutjanidae	−0.16
	Yellowtail snapper	Rubia	Lutjanidae	0.80
Crabs	Stone crab	Cangrejo moro	Menippidae	−0.61
Mullets	Bobo mullet	Bobo	Mugilidae	−0.44
	Fantail mullet	Lisa amarilla	Mugilidae	−0.75
	Common mullet	Lisa	Mugilidae	0.18
	Hospe mullet	Lebrancha	Mugilidae	0.57
Oysters	American oyster	Ostion	Ostreidae	0.31
Skates	Roundel skate	Raya	Rajidae	−0.40
Croakers	Ground croaker	Ronco	Sciaenidae	−0.01
	Seatrout	Corvina	Sciaenidae	0.59
	Kingcroaker	Ratón	Sciaenidae	0.80
	Atlantic croaker	Gurrubata	Sciaenidae	−0.03
Mackerels	Atlantic bonito	Bonito	Scombridae	0.45
	King mackerel	Carito o peto	Scombridae	0.41
	Spanish mackerel	Sierra	Scombridae	0.02
Groupers	Jewfish	Cherna	Serranidae	0.86
	Black grouper	Abadejo	Serranidae	−0.11
	Red grouper	Mero	Serranidae	0.54
Porgies	Sheepshead sea bream	Sargo	Sparidae	0.20
	Sea bream	Postha	Sparidae	−0.47
	Yellow sea chub	Chopa	Sparidae	0.90
Others	Great barracuda	Picuda	Sphyraenidae	0.59
	Atlantic cutlassfish	Cintilla	Trichiuridae	0.13
	Ladyfish	Macabi	Elopidae	0.20
	Hogfish	Boquinete	Labridae	0.52
	Tropical gar	Pejelagarto	Lepisosteidae	0.77
	Cobia	Cobia	Rachycentridae	−0.51

Factor loadings on the first principal component (PC1) from the 46 commercial landings are shown

2005). Satellite-derived products (Chl-a mg m^{-3}, NPP g C m^{-2} day^{-1}, and SST°C) were evaluated in the southwestern Gulf of Mexico (Fig. 1). Monthly satellite-derived SST data (1985–2006) from the AVHRR Pathfinder v5 were evaluated. The mean annual cycle for 1985–2006 and monthly SST anomalies (expressed as the difference from the long-term mean SST of the same period) were calculated for the study area. The seasonal distribution of the warm pool (SST > 28.5°C) was reviewed as well as the large event of 1998, calculating the area (km^2) with SST > 28.5°C. The Chl-a, using the standard, maximum-band ratio algorithms, was derived from the OCTS and SeaWiFS sensors for 1997–2006. The NPP was calculated from the satellite-derived Chl-a, photosynthetically available radiation, and the AVHRR Pathfinder v5 SST using the Vertically Generalized Production Model of Behrenfeld and Falkowski (1997). Monthly anomalies of the Chl-a and NPP were calculated as the ratio of a current value to the corresponding long-term monthly mean (1997–2006) and then expressed as percentage anomaly, i.e., 100*(Anomaly-1). Satellite data were processed using the Wim Software version 6.5 (http://wimsoft.com/).

A number of methods are available to detect abrupt changes in a time-series (see Hare & Mantua, 2000; Mantua, 2004; Rodionov, 2004; Litzow, 2006). Two methods were used to identify changes in fishery landings and satellite-derived time-series. A principal component analysis (PCA) was made on commercial landings. The PCA is a useful method to extract common patterns of variation and also needs no a priori assumption about the shift years. A number of methods to determine the statistical significance of the modes to be retained have been derived, i.e., Rule N, Scree test, and Guttman criterion. Here, the method of North et al. (1982) was used, keeping only the modes with an eigenvalue separated from an adjacent eigenvalue by more than the sampling error. The Rodionov method was later used to detect abrupt changes in fishery landings and ocean-color time-series. This method also requires no initial visual inspection of the time-series (Rodionov, 2004). Monthly precipitation data at Ciudad del Carmen, Campeche (1997–2003; data distributed by Comisión Nacional del Agua), weekly maps of the sea level anomaly (SLA) merged from TOPEX-POSEIDON, Jason, and ERS-1/2 data (processed by SSALTO-DUACS and distributed by AVISO) were included because those variables (high rainfall and negative SLA) are known to be related with increased productivity caused by the increase in the nutrient flux to surface waters (Yoder & Kennelly, 2003; Kahru et al., 2007).

Results

The mean annual cycle of the SST (1985–2006) is shown in Fig. 2. The SST > 28.5°C was recorded from July to September. The lowest values were in January and February (SST ~ 24.5°C). A satellite-derived composite image of July to September shows the climatological SST (1985–2006) > 28.5°C (covering an area of 6,742,753 km^2), which defines the WHWP (Fig. 3A). According to Wang et al. (2006), a warm pool 25% larger than the climatological area is defined as a large warm pool. The large area of the WHWP in 1998 (July-September) was detected (Fig. 3B, 11,858,550 km^2 with SST > 28.5°C) showing that it was ~76% larger than climatological SST. The monthly comparison (July–September) between climatological and the large warm pool event of 1998 showed that the spatial extension (area with SST > 28.5°C) was 190% larger during July that year (Fig. 4).

During 1997 and 2003, the highest rainfall peaks were lower than any other peak during 1998 and 1999 with highest values observed during 2000 and 2001 (Fig. 5). In addition, positive sea level anomalies (SLA, Fig. 6) were recorded in SWGM during late 1998.

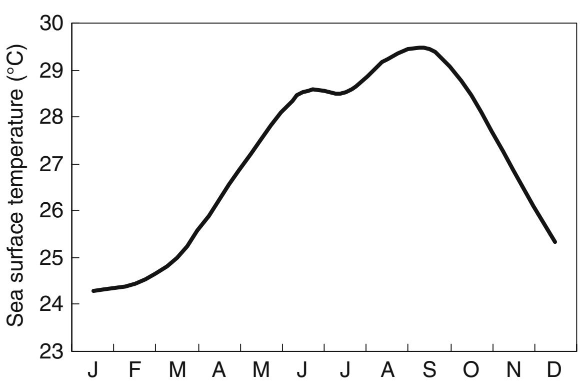

Fig. 2 Mean annual cycle of sea surface temperature (AVHRR Pathfinder v5, 1985–2006)

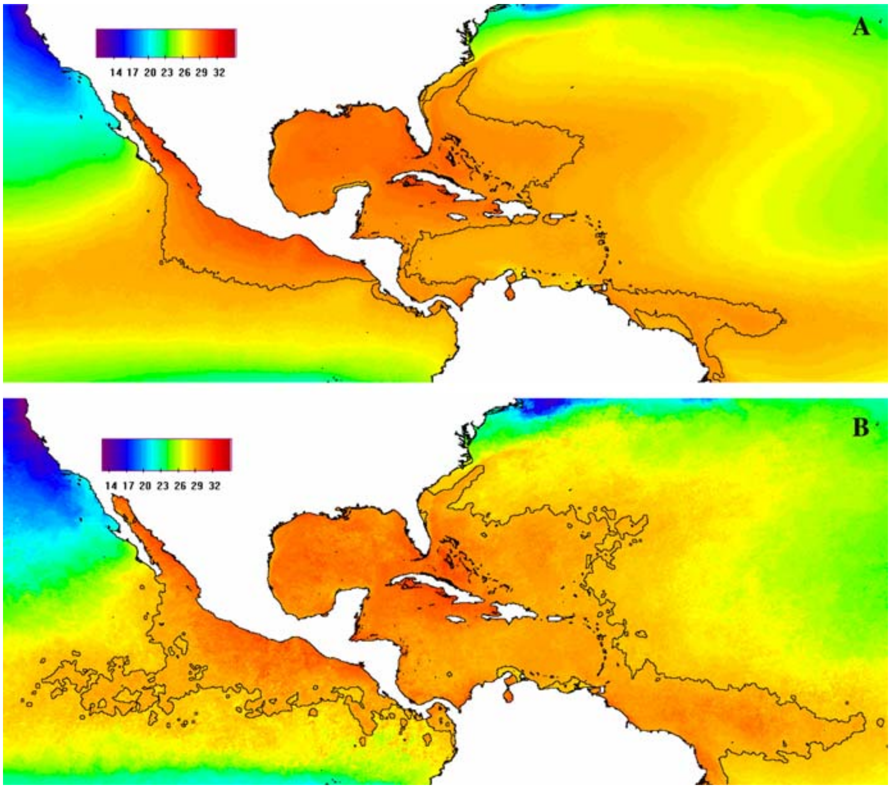

Fig. 3 Composite images (July–September) derived from the AVHRR Pathfinder v5.0 showing areas with SST warmer than 28.5°C (black contours). Panel **A** corresponds to the climatological SST (1985–2006) and panel **B** shows the large warm-pool event of 1998

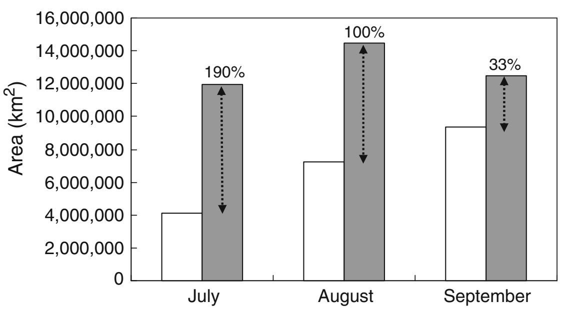

Fig. 4 Area (km^2) with SST warmer than 28.5°C during July–September comparing the climatological (white bars) and large event of 1998 (gray bars) and showing the percentage difference (arrows)

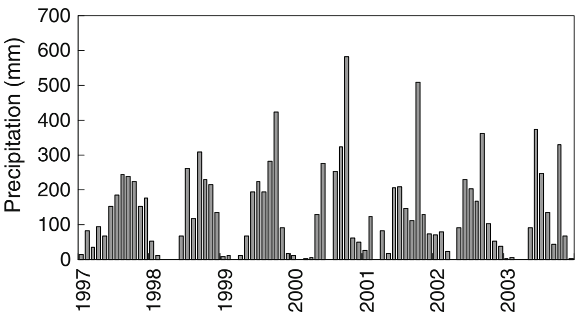

Fig. 5 Monthly precipitation in Ciudad del Carmen, Campeche, Mexico (1997–2003)

The shift detection method suggested that 1997–1999 was characterized by positive SST anomalies (Fig. 7). Such a warm SST state was most evident during May 1998 and October 1999 with persistent, positive SST anomalies, whereas colder than average conditions dominated during 2000 and 2001 (Fig. 7). A shift from a warm to a cool state was suggested to occur around 2000, followed by warm (2002–2004) and cold (2005–2006) conditions (Fig. 7).

The shift detection method suggested periods of prevailing negative anomalies of the NPP (1997–1999 and 2002–2006), with 2000–2001 mostly characterized by positive NPP anomalies and precipitation greater than any other peak during 1997 and 2003 (Figs. 5, 8). The warm SST in 1997–1999 and its impact on biological productivity were more evident in the NPP than in Chl-a anomalies (Fig. 8), because the shift of 2000 was not detected in the Chl-a anomalies (Fig. 8, panel A). However, the Chl-a anomalies showed a negative trend during 1998 until middle 1999 followed by an increasing trend during

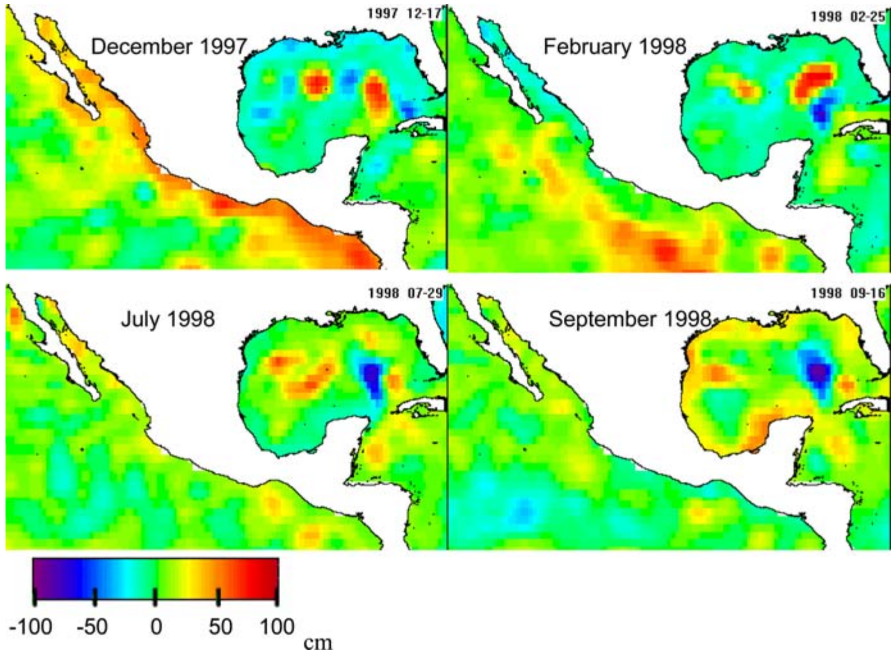

Fig. 6 Weekly maps of the sea level anomaly merged from TOPEX-POSEIDON, Jason, and ERS-1/2 satellites. Maps show the evolution of the ENSO signal in the Eastern Pacific. Positive SLA anomalies were detected in the SWGM during late 1998 (lower-right panel). Data were created by SSALTO-DUACS and distributed by AVISO

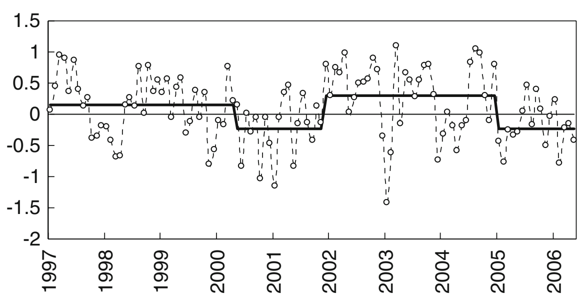

Fig. 7 Monthly anomalies of the SST in the SWGM. Steps derived from the Rodionov method (bold line) are shown

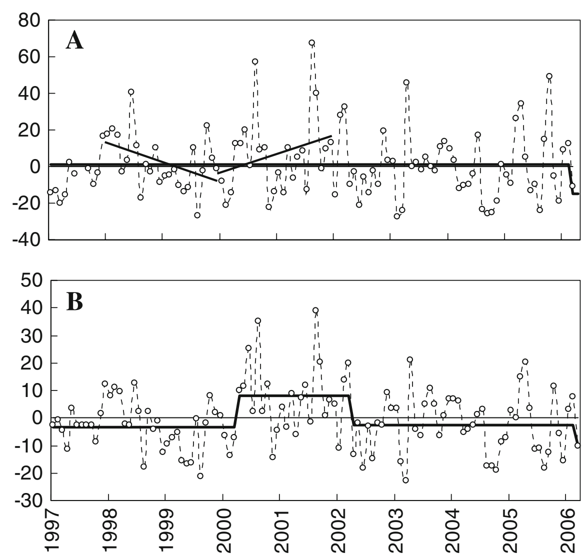

Fig. 8 Monthly anomalies (%, 1997–2006) of chlorophyll *a* (panel **A**, 1998–2001 and net primary productivity (panel **B**) in the SWGM. Linear trends (panel **A**) and steps derived from the Rodionov method (bold line) are also shown

2000 and 2001. The period 2000–2003 was also characterized by a higher frequency of hurricanes in the Atlantic and tropical storms in the SWGM (Table 2).

Capture per unit of effort (CPUE) is commonly used as an index of abundance; however, the lack of fishing effort data added some limitations to our analysis (we were not able to discuss how fishing pressure is forcing the dynamics of the species and this needs further research). Nevertheless, the first principal component (PC1) (Fig. 9, upper panel) derived from the record of 46 monthly commercial landings (Table 1) showed coherence with environmental data and with individual species (Fig. 9). According to the method of North (1982), only one mode was retained (not shown). The PC1 isolated the most important pattern of common variability (25% of explained variance) suggesting two distinct periods, 1997–1999 (negative scores) and 2000–2003 (positive scores), which suggests a shift during 2000 as seen by Chl-a, NPP, and SST. The shift around 2000 was also detected in four fisheries with commercial importance in the SWGM (Fig. 9).

Table 2 Hurricane and storm frequency in the SWGM and total number recorded in the Atlantic Region (including the Western Atlantic, Caribbean Sea, and the Gulf of Mexico except the SWGM) during 1997 and 2006

Year	SWGM	Atlantic region (total)
1997	–	8
1998	1 (Mitch, TS)	14
1999	–	16
2000	1 (Keith, TD)	18
2001	1 (Chantal, TD)	17
2002	1 (Isidore, H3)	14
2003	1 (Larry, TS)	21
2004	–	18
2005	1 (Stan, TS)	30
2006	–	9

Data were made available by Servicio Meteorologico Nacional (http://smn.cna.gob.mx/)

TS: tropical storm

TD: tropical depression

H3: Hurricane of category 3 (Saffir-Simpson scale)

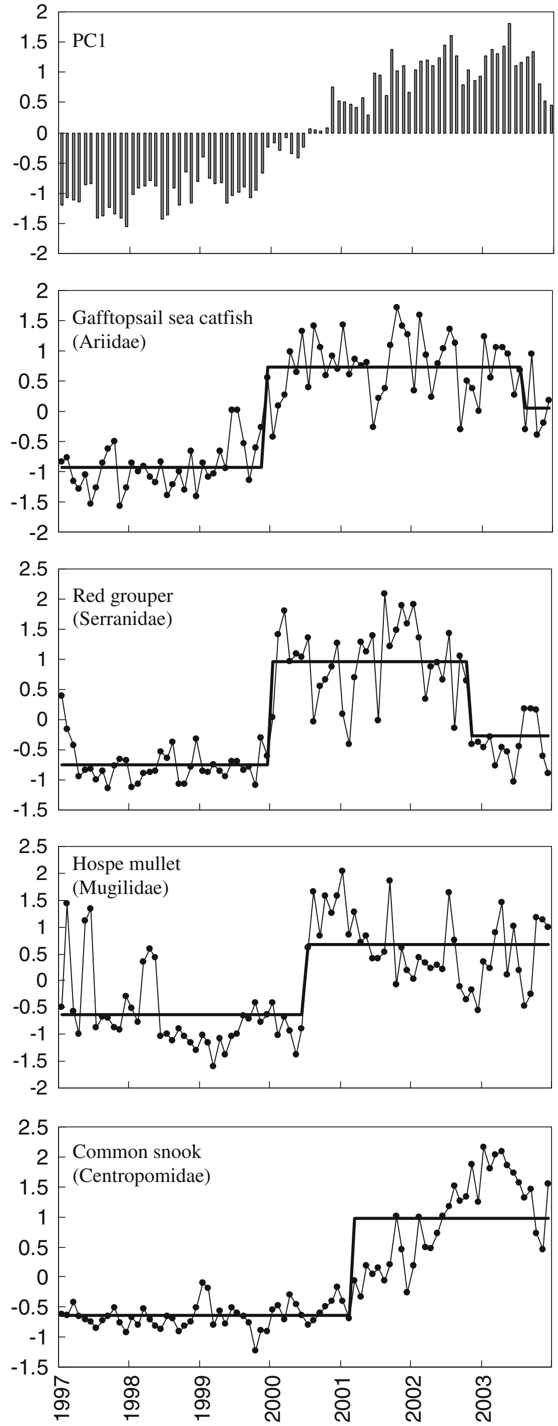

Fig. 9 First principal component scores (upper panel, 25% of explained variance) from a principal component analysis of the 46 standardized fishery landings. Other panels show the detected shift around the year of 2000 in some fisheries with commercial importance

Discussion

The ocean-color era started with the launch of the Coastal Zone Color Scanner in 1978. In addition, data from satellites launched later have been used to study marine basins by providing a unique approach to study near-surface phytoplankton, primary productivity, biogeochemical cycles, and linkages to fishery research (O'Reilly et al., 1998).

Satellite estimates of SST, e.g., those available by the Advanced Very High Resolution Radiometer, AVHRR, have wide applications in Fishery Oceanography, because the SST is an important environmental factor influencing distribution patterns and growth of marine fish populations (Dower et al., 2000). As discussed hereafter, satellite data showed a shift between a warm SST and poor productivity (1997–1999) followed by a cooler SST and high productivity (2000–2001) that could force significant changes in the higher trophic levels.

Large warm pools are known to cause a multitude of changes in oceanic-atmospheric conditions and some have been linked to the ENSO forcing the following summer, e.g., the ENSO 1997–1998. Additional larger events occurred in 1958, 1969, 1983, and 1987 (see Wang et al., 2006). Large warm pools also occurred during non-ENSO years, i.e., 1952, 1980, 1990, 1995, 1997, 1999, 2000, 2001, and 2002; see Enfield et al., 2006; Wang et al., 2006. The ENSO forcing in the tropical Atlantic and the IAS region has been discussed since the late 1980s, especially in relation to rainfall anomalies (Ropelewski and Halpert, 1986; Vega et al., 1998; Giannini et al., 2000). Wang and Enfield (2003) discussed how the ENSO signal is transferred to the Atlantic during the winter preceding some large warm pools when the Hadley cell weakens and causes warming of the warm pool the following summer. They also noted that a decrease in sea level pressure (SLP) anomalies and an anomalous increase in atmospheric convection and cloudiness are associated. Those conditions result in less longwave-radiation loss from the sea surface, which then reinforces the SST anomalies (Wang and Enfield, 2003). The large warm pool of 1998 was evident in three-month (July–September) composite images of the SST that year, showing that its actual area is larger than its climatological area by ~76% (Fig. 3), however, the monthly comparison between the climatological and the warm event of 1998 (Fig. 4) showed that during July that year the area was 190% larger; however, Wang and Enfield (2003) reported that the area of the warm pool during large events (calculated by averaging over the warm years of 1958, 1969, 1983, 1987, and 1998) increased by 96% the same month.

Negative anomalies of the SLP and positive SST anomalies are atmospheric-oceanic conditions related to an increase of hurricane activity in the IAS and the Atlantic (see Babin et al., 2004; Wang et al., 2006) during a large WHWP. During the large warm pool of 1998, 14 hurricanes and tropical storms were recorded in the Atlantic and surrounding areas (Table 2), though only one hurricane impacted the SWGM (hurricane Mitch was classified as a category 5 on the Saffir-Simpson scale; however, it reached the SWGM as a tropical storm).

After the warm and low productivity period of 1997–1999, a cooler SST was measured during 2000 and 2001 coinciding with high rainfall with values greater than any maximum in 1997–2003 (Fig. 5). Wang et al. (2006) noted that during August and October, large warm pools and a warm TNA are associated with increased rainfall over the Caribbean, Mexico, the eastern subtropical Atlantic, and the southeastern Pacific. The lower precipitation recorded during 1997 and 1999 (the rainfall maxima during that period were lower than any peak in 1997–2003; Fig. 5) might correspond to an ENSO-related rainfall correlation, which has been found negative by other studies over the Caribbean, the Pacific side of Central America, and the southeastern Pacific (Wang et al., 2006); however, it is not reviewed here and needs further research. In addition to increased rainfall, the cooling of the SST during 2000 and 2001 (August–October) might also be explained by the passage of tropical storms Keith (2000) and Chantal (2001), both crossing the SWGM. Both years were also characterized by a high number of hurricanes and tropical storms on the Atlantic side (Table 2). Such events are known to increase near-surface Chl-a and NPP in response to curl-induced upwelling and increased upper ocean cooling (Babin et al., 2004). Melo et al. (2000) found similar conditions (an increased frequency of storms associated with a high concentration of pigments) during the ENSO 1982 and 1983 (which had another large warm pool linked to an ENSO) around Cuba and other areas in the IAS. The opposite response in the SWGM seen during the large warm pool of 1997 to 1999 might be related to additional dynamics caused by the dynamics of the Loop Current and its eddies. It is known that of cyclonic and anticyclonic eddies often occur in this area, many of them impacting the Mexican Continental Shelf. Zavala-Hidalgo et al. (2003) reported a long-lived cyclonic eddy that merged with other eddies at least three times from February 1998 to April 1999 near northwestern Cuba, as shown in Fig. 6. In contrast, positive SLA anomalies were found in the SWGM during late 1998 by visual examination (Fig. 6). As discussed by Kahru et al. (2007:2–3, Figs. 1, 4), a positive SLA (a proxy for anticyclonic eddies) is associated with a deeper thermocline (and an associated nutricline) and a reduced Chl-a caused by decreased phytoplankton growth. Those conditions of a positive SLA and the positive SST anomalies in the SWGM during the large warm-pool event of 1998 might be a likely explanation of the low productivity found especially that year. The almost zero number of meteorological phenomena during 1997 and 1999 (Table 2) in the SWGM might be additional explanations of the low productivity state of the environment.

Though our analysis was limited by the scarcity of the available commercial landings and the lack of information on the fishing effort, the shift detected in fishery landings during 2000 (PC1, Fig. 9) showed coherency with the warm and low productivity episode of 1997–1999 and the following cooling conditions during 2000 and 2001 as likely explanations of an environmental forcing in fishery populations during those periods. Results for individual landings (with commercial importance in the SWGM) also suggested that a shift occurred around 2000 (Fig. 9). Spawning migrations of the hospe mullet (Mugilidae) have been linked to changes in the SST. Ibañez & Gutierrez-Benitez (2004) found a negative and significant correlation between spawning migrations of this pelagic species and water temperature (Pearson $r = -0.77$), noting that an optimum range is reached when the SST is 23–26°C. The development of the warm pool might correspond to unfavorable conditions for spawning, whereas it is possible that optimum conditions were prevalent during the following cold period as suggested by the detected shift (Fig. 9). Such conditions might also explain the shift observed for other species. The common snook (Centropomidae) and the gafftopsail catfish (Ariidae) are demersal species with commercial importance in the SWGM (Fig. 9). Their life cycles are linked to estuarine systems and coastal areas for feeding, recruitment, growth, reproduction, and spawning (see Yáñez-Arancibia & Lara-Dominguez, 1988). Aliaume et al. (2000) found a slower growth for the common snook when food depletion, lower water quality, and habitat reduction occur in tropical areas. The depleted habitat during 1997 and 1999 could cause unfavorable conditions affecting some stages of the life cycle of those species.

Evidence derived from other studies was found related to the discussed change from warm to cold conditions and its effects on marine organisms. Pascual et al. (2003) found that males of the white shrimp *Litopenaeus setiferus* (a species which is commonly found as part of the benthic community structure in the SWGM) are vulnerable when the SST is >28°C because those conditions affect their physiological, immunological, and reproductive conditions, and they reported a deterioration of spermathopores during 1998. Commercial landings for this species were ~76 to 122 t for 1995–1997 and decreased to ~28 t during 1998 (Sub-Delegación de Pesca, Campeche). The reproductive condition of this species was reported to be healthy in 2001, matching with the cold period discussed in our work.

Long-term trends have also been estimated for the red grouper (Serranidae, a demersal-pelagic species). Annual yields of the red grouper have shown a long-term decrease in the SWGM (Burgos & Defeo, 2004) mostly related to overfishing. However, the authors also discussed that such fluctuations might be related to environmental or anthropogenic forcing, e.g., oil spills in the SWGM. Giménez-Hurtado et al. (2005) found that recruitment of this species decreased after 1997 for individuals of age 1 and 2. The standardized landings for the red grouper suggested an inverse relationship between the detected shifts; more (less) landings during the cold (warm) periods (Fig. 9). It is possible that large warm-pool events in the past, e.g., the strong events of 1983 and 1987, would give important evidence about the environmental forcing on groupers.

Conclusions

Studies involving multispecies and multigear fisheries are too complex to be easily compared, especially when trying to separate the anthropogenic, i.e., overfishing, coastal pollution, habitat alteration, etc., from naturally occurring environmental shifts. Nevertheless, we did find empirical evidence that a large warm pool linked with a strong ENSO occurring the previous year in the Pacific, e.g., the large warm pool of 1998, yielded a strong negative biological response (fishery landings, Chl-a, and the NPP) in the SWGM. The opposite response was found during other large warm-pool events occurring during non-ENSO years, e.g., 2000–2001. In addition, it is evident that large warm pools not linked with ENSO events also have a strong influence on the biological component in the SWGM. Future contributions predicting the development of large warm pools may help to take actions to ensure a sustained-yield management in the SWGM.

Acknowledgements We thank NASA Ocean Color Processing Group, NASA GSFC, PODAAC, and AVISO for satellite data. MMS is a doctoral student at CIBNOR on scholarship (CONACYT 166339). We thank Sub-Delegación de Pesca (Campeche) and Dr. Abraham Navarrete del Proó for making available the fishery landings in the SWGM. Thanks to Dr. Ellis Glazier who edited this English-language text.

References

Aliaume, C., A. Zerbi, J. C. Joyeux & J. M. Miller, 2000. Growth of juvenile *Centropomus undecimalis* in a tropical island. Environmental Biology of Fishes 59: 299–308.

Arreguín-Sánchez, F. & S. Manickchand-Heileman, 1998. The trophic role of lutjanid fish and impacts of their fisheries in two ecosystems in the Gulf of Mexico. Journal of Fish Biology 53: 143–153.

Arreguín-Sánchez, F. & E. Arcos-Huitrón, 2007. Fisheries catch statistics for Mexico. In Zeller, D. and D. Pauly (eds), Reconstruction of marine fisheries catches for key countries and regions (1950–2005). Fisheries Centre Research Reports, 15(2). Fisheries Centre, University of British Columbia: 81–103.

Arreguín-Sánchez, F., M. J. Zetina-Rejón, S. Manickchand-Heileman, M. Ramírez-Rodríguez & L. Vidal, 2004. Simulated response to harvesting strategies in an exploited ecosystem in the southwestern Gulf of Mexico. Ecological Modelling 172: 421–432.

Babin, S. M., J. A. Carton, T. D. Dickey & J. D. Wiggert, 2004. Satellite evidence of hurricane-induced phytoplankton blooms in an oceanic desert. Journal of Geophysical Research 109: C03043. doi:10.1029/2003JC001938.

Bakun, A. & K. Broad, 2003. Environmental 'loopholes' and fish population dynamics: comparative pattern recognition with focus on El Niño effects in the Pacific. Fisheries Oceanography 12: 458–473.

Behrenfeld, M. J. & P. G. Falkowski, 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceanography 42: 1–20.

Behrenfeld, M. J., R. O'Malley, D. Siegel, C. McClain, J. Sarmiento, G. Feldman, A. Milligan, P. Falkowski, R. Letelier & E. Boss, 2006. Climate-driven trends in contemporary ocean productivity. Nature 444: 752–755.

Burgos, R. & O. Defeo, 2004. Long-term population structure, mortality and modeling of a tropical multi-fleet fishery: The red grouper *Epinephelus morio* of the Campeche Bank, Gulf of Mexico. Fisheries Research 66: 325–335.

Chavez, F. P., P. G. Strutton, G. E. Friederich, R. A. Feely, G. C. Feldman, D. G. Foley & M. J. McPhaden, 1999. Biological and chemical response of the equatorial Pacific Ocean to the 1997–98 El Niño. Science 286 (5447): 2126. doi:10.1126/science.286.5447.2126.

Chavez, F. P., J. Ryan, S. E. Lluch-Cota & M. Niquen, 2003. From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. Science 299: 217–221.

Dower, J., W. Leggett & K. Frank, 2000. Commentary: Improving fisheries oceanography in the future. In Harrison & Parsons (eds), Fisheries Oceanography, An Integrative Approach to Fisheries Ecology and Management. Fish and Aquatic Resources Series 4. Blackwell Science, Oxford: 263–281.

Enfield, D. B., S. K. Lee & C. Wang, 2006. How are large Western Hemisphere Warm Pools formed? Progress in Oceanography 70: 346–365.

Giannini, A., Y. Kushnir & M. A. Cane, 2000. Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. Journal of Climate 13: 297–311.

Giménez-Hurtado, E., R. Pérez-Puelles, S. E. Lluch-Cota, A. González-Yañez, V. Moreno-García & R. Burgos de la Rosa, 2005. Historical biomass, fishing mortality, and recruitment trends of the Campeche Bank red grouper (*Epinephelus morio*). Fisheries Research 71: 267–277.

Hare, S. R. & N. J. Mantua, 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47: 103–146.

Ibañez, A. L. & O. Gutierrez-Benitez, 2004. Climate variables and spawning migrations of the striped mullet and white mullet in the north-western area of the Gulf of Mexico. Journal of Fish Biology 65: 822–831.

Kahru, M., P. C. Fiedler, S. T. Gille, M. Manzano & B. G. Mitchell, 2007. Sea level anomalies control phytoplankton biomass in the Costa Rica Dome area. Geophysical Research Letters 34: L22601. doi:10.1029/2007GL031631.

Kahru, M. & B. G. Mitchell, 2000. Influence of the 1997–98 El Niño on the surface chlorophyll in the California Current. Geophysical Research Letters 27(18): 2937–2940.

Litzow, M., 2006. Climate regime shifts and community reorganization in the Gulf of Alaska: how do recent shifts compare with 1976/1977? ICES Journal of Marine Science 63: 1386–1396.

Mantua, N. J., 2004. Methods for detecting regime shifts in large marine ecosystems: a review with approaches applied to North Pacific data. Progress in Oceanography 60: 165–182.

Melo, N., F. Müller-Karger, S. Cerdeira, R. Perez, I. Victoria Del Rio, P. Cardenas & I. Mitrani, 2000. Near-surface phytoplankton distribution in the western Intra-Americas Sea: The Influence of El Niño and weather events. Journal of Geophysical Research 105: 14029–14043.

Nixon, S. W., 1988. Physical energy inputs and the comparative ecology of lake and marine ecosystems. Limnology Oceanography 33(4, part 2): 1005–1025.

North, G. R., T. L. Bell, R. F. Calahan & F. J. Moeng, 1982. Sampling errors in the estimation of empirical orthogonal functions. Monthly Weather Review 110: 699–706.

O'Reilly, J. E., S. Maritorena, B. G. Mitchell, D. A. Siegel, K. L. Carder, S. A. Garver, M. Kahru & C. McClain, 1998. Ocean color chlorophyll algorithms for SeaWiFS. Journal of Geophysical Research 103: 24, 937–24, 953.

Pascual, C., A. Sánchez, F. Vargas-Albores, G. LeMoullac & C. Rosas, 2003. Haemolymph metabolic variables and immune response in *Litopenaeus setiferus* adult males: The effect of an extreme temperature. Aquaculture 218: 637–650.

Ramírez-Rodríguez, M., E. A. Chávez & F. Arreguín-Sánchez, 2000. Perspective of the pink shrimp (*Farfantepenaeus duorarum* Burkenroad) fishery of Campeche Bank, Mexico. Ciencias Marinas 26: 97–112.

Ramírez-Rodríguez, M., F. Arreguín-Sánchez & D. Lluch-Belda, 2003. Recruitment patterns of the pink shrimp *Farfantepenaeus duorarum* in the southern Gulf of Mexico. Fisheries Research 65: 81–88.

Rodionov, S., 2004. A sequential algorithm for testing climate regime shifts. shifts. Geophysical Research Letters 31: L09204.

Ropelewski, C. F. & M. S. Halpert, 1986. North American precipitation and temperature patterns associated with the

El Niño/Southern Oscillation (ENSO). Monthly Weather Review 114: 2352–2362.

Vega, A., R. Rohli & K. Henderson, 1998. The Gulf of Mexico mid-tropospheric response to El Niño and La Niña forcing. Climate Research 10: 115–125.

Vidal-Hernández, L. & D. Pauly, 2004. Integration of subsystem models as a tool toward describing feeding interactions and fisheries impacts in a Large Marine Ecosystem, the Gulf of Mexico. Ocean and Coastal Management 47: 709–725.

Wang, C. & D. B. Enfield, 2001. The tropical Western Hemisphere Warm Pool. Geophysical Research. Letters 28(8): 1635–1638.

Wang, C. & D. B. Enfield, 2003. A further study of the Tropical Western Hemisphere Warm Pool. Journal of Climate 16: 1476–1493.

Wang, C., 2005. ENSO, Atlantic climate variability, and the Walker and Hadley circulations. In Diaz, H. F. & R. S. Bradley (eds), The Hadley Circulation: Present, Past and Future. Kluwer Academic Publishers: 173–202.

Wang, C., D. B. Enfield, S. K. Lee & C. W. Landsea, 2006. Influences of the Atlantic warm pool on western hemisphere summer rainfall and Atlantic hurricanes. Journal of Climate 19: 3011–3028.

Yáñez-Arancibia, A. & A. Lara-Dominguez, 1988. Ecology of three sea catfishes (Ariidae) in a tropical coastal ecosystem-southern Gulf of Mexico. Marine Ecology Progress Series 49: 215–230.

Yoder, J. A. & M. A. Kennelly, 2003. Seasonal and ENSO variability in global ocean phytoplankton chlorophyll derived from 4 years of SeaWiFS measurements. Global Biogeochem. Cycles 17(4), doi:10.1029/2002GB001942.

Zavala-Hidalgo, J., S. L. Morey & J. J. O'Brien, 2003. Cyclonic eddies northeast of the Campeche Bank from altimetry data. Journal of Physical Oceanography 33: 623–629.