Variability of the thermohaline structure in the northern Veracruz Coral Reef System, Mexico

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ABSTRACT

The variability of the thermohaline fields is studied at different time scales in the Veracruz Coral Reef System (VCRS) with hydrographic data from eleven CTD campaigns carried out from 2006 to 2010 and time series of temperature obtained from a mooring array (22 months) and from a current profiler (21 months). Results show that, from October to March, the vertical structure of temperature was quasi-homogeneous, with temperature differences between surface and bottom waters of less than 0.5°C, and temperature inversions were frequently observed. By contrast, strong stratification was observed in late spring and summer when the surface—bottom temperature difference can be larger than 8°C. In some years, the lower bottom temperatures were observed during summer. The lower temperatures of the 2007–2010 period were observed during winter 2010, being 2°C to 4°C lower than those observed in the previous years. It was also the year showing more temperature variability during the summer months due to several atmospheric tropical systems that affected the region, like tropical cyclone Alex. The dominant water mass at the VCRS observed during the study period was the Gulf Common Water, with salinities lower than 36.5 psu and temperatures between 21.2°C and 30.0°C. In addition, during summer, high temperature and low salinity water from local rivers was observed in the upper 6 m. During autumn-winter, low temperature and salinity waters coming from the northwestern shelves of the Gulf were observed.

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1. Introduction

The VCRS is a 400 km² marine protected area located offshore of the City of Veracruz and the Boca del Río and Anton Lizardo municipalities. The continental shelf in the VCRS area is narrow, around 33 km wide, and the reefs are located between the shoreline and the 40 m isobath. The marine floor is complex, with shallow sand banks, reefs and islands that form several channels with variable dimensions and depths (Fig. 1). The VCRS includes two groups of reefs, one composed of 12 reefs and located to the north, and the other one composed of 11 reefs and located to the southeast of the City of Veracruz (Lara et al., 1992). This study is focused on the description of the thermohaline fields of the northern group of reefs and its variability in different time scales.

The circulation in the VCRS has an important seasonality. During autumn–winter, the currents are strongly influenced by cold fronts coming from the continental United States and during summer by southeasterly winds. In previous studies, that include the entire Tamaulipas and Veracruz shelf, a seasonality in the currents was identified based on numerical simulations, showing clockwise mean currents between May and August and counterclockwise from September to March (Zavala-Hidalgo et al., 2003; Morey et al., 2005).

A peak in the energy spectra of the winds in the meteorological synoptic scale (2–10 days), which mainly determine the currents in the VCRS, has been observed (Allende-Arandía, personal communication). It was also observed that, for the year 2009 (2010), 49% (60%) of the time the currents flowed southeastward, reaching magnitudes of more than 0.5 m s⁻¹ and, in some cases, up to 1 m s⁻¹. These episodes of strong southeastward currents were associated with northers that lasted from two to five days. On the other hand, weaker northwestward currents occurred 51% (40%) of the time, with velocities lower than 0.3 m s⁻¹ most of the time.

Along the coast of Veracruz, low sea surface temperatures (SSTs) have been observed compared to those offshore. From July to September, the low SSTs are associated with coastal upwelling due to southeasterly winds, and between September and March they are associated with the advection of cool water from the Texas–Louisiana shelf, coming along the inner and middle shelves (Zavala-Hidalgo et al., 2006).

There are few studies in the VCRS. Carrillo et al. (2007), based on large scale atlases (Slutz et al., 1985; Da Silva et al., 1994), reported an annual mean SST in the VCRS of 26.6°C, with a
maximum of 29.4 °C and a minimum of 22.9 °C; an annual mean salinity of 35.98 psu, and an annual mean air temperature at surface (2 m) of 26.0 °C, with a maximum of 29.2 °C and a minimum of 21.8 °C. The rainy season is from June to October, with maximum precipitation observed in September, and the dry season is in spring, being April the driest month; the annual average of precipitation is 821.4 mm. The mean wind speed in the region is 5.51 m s$^{-1}$, with a predominant northeasterly direction. Salas-Pérez and Arenas-Fuentes (2011) describe the water masses observed in two surveys, with a week of difference, and show a decrease in temperature and salinity due to the influence of a norther that affected the VCRS in February 2005.

Here, a detailed hydrographic study of the VCRS is presented, including its variability in different time scales: interannual, seasonal and intraseasonal. Data and methods are described in Section 2 and the results of the study, including the analysis and discussion of the variability for the temperature, winds, heat content, currents, and thermohaline structure of the waters in the VCRS are included in Section 3. Final remarks are provided in Section 4.

2. Data

Data sets from different sources are used for the analysis and are described next.

2.1. Currents and temperature data

Data from a Nortek Aquadopp Profiler current meter (600 kHz), located between the Anegada de Adentro and Isla Verde reefs at 30-m depth (Fig. 1), are analyzed. The instrument was programmed to sample currents, temperature and pressure every 30 min. Oceanographic campaigns were carried out every two or three months to replace the current meter with another instrument having the same configuration. The temperature sensor of the current meter has a resolution of 0.1 °C. A thermistor array was installed at the same location, composed of 8 sensors: five HOBO U22 temperature sensors, with a resolution of 0.02 °C, and three HOBO U20 pressure–temperature sensors, with a resolution of 0.04 kPa and 0.1 °C, respectively. These sensors were programmed to sample every 10 min at approximately 5, 11, 17, 22 and 27 m depth. Thermistors were also installed in a site around 200 m south of Isla Verde at ~1.5 m depth.

2.2. Hydrographic and SST data

Eleven CTD campaigns were carried out; the first two were conducted along transects that were slightly different from that followed in the last nine (Fig. 1, Table 1). The CTD used in the 2006 campaign was a Seabird 37 MicroCat, while a SeaBird 19plus V2 was used in the other campaigns. The sensors have a resolution of 0.005 °C in temperature and resolves 0.4 ppm in salinity. Satellite SSTs derived from the Advanced Very High Resolution Radiometer (AVHRR) [http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/available.html], with a 0.25-degree resolution in latitude and longitude and daily frequency, were also analyzed. The nearest ocean grid point to the current meter location was chosen and the SST time series for the period 2007–2010 extracted.
2.3. Wind data

The wind stress and the along-coast wind stress component were computed based on the North American Regional Reanalysis (NARR) 10-meter wind data for the period 2007–2010 [http://nomads.ncdc.noaa.gov/#narr_datasets]. This 3-hourly dataset has a spatial resolution of 32 km. The along-coast wind stress component was computed based on a smoothed 20 m isobath to analyze its contribution to the observed variability.

3. Results

3.1. Annual cycle of temperature

In order to describe the annual cycle of temperature in the VCRS, the AVHRR-SST data together with the thermistor time series at 5 m, 11 m, 17 m, 22 m, and 27 m depth, and the temperature measured with the ADCP at 30 m depth during 2009, are used (Fig. 2). This year was chosen since there are few gaps in the thermistor and ADCP datasets.

Measurements show that the water column is almost homogeneous from October to February, when temperature differences between surface and bottom are less than 0.5 °C, except for a stratification episode occurred between late September and early October (Fig. 2). During spring and summer the water column is stratified, with surface–bottom temperature differences of up to 8 °C. The lower (higher) bottom temperature was observed in July (late September) and the lower (higher) temperature at the surface occurred in December (August). A summary of the annual minimum, maximum and mean temperatures observed at the surface and bottom from 2007 to 2010, along with the month of occurrence, is presented in Table 2.

The low temperature at the bottom observed in July, that was lower than that in winter, can be caused by the upwelling-favorable winds observed from April to early September. Zavala-Hidalgo et al. (2006), based on monthly satellite SST images, show that along the Tamaulipas–Veracruz inner shelf, there are relatively low SSTs in summer of around 1 to 2 °C lower than those observed ~50 km offshore. However, our high frequency data does not show a marked decrease of the upper layer temperatures like that caused by strong upwelling events, suggesting that there

<table>
<thead>
<tr>
<th>CTD surveys</th>
<th>Temperature ADCP</th>
<th>Thermistor array</th>
<th>Surface thermistor</th>
<th>NARR winds and AVHRR SST</th>
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<tr>
<td>30 Jun 2009</td>
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<td></td>
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</tbody>
</table>

Fig. 2. Annual cycle of temperature in the northern Veracruz Coral Reef System (see Fig. 1 for location of the site): sea surface temperature derived from AVHRR (green); temperature measured with the thermistor array at 5 m (black), 11 m (segmented red), 17 m (red), 22 m (segmented blue), and 27 m (blue); temperature measured with the ADCP at 30 m (purple).
is a near balance between the entrance of cool bottom water and a positive surface heat flux. In addition to the upwelling condition, the entrance of low-temperature water into the bottom layers may also be favored by bottom layer friction and internal waves. There is a high frequency variation of the bottom temperature which suggests the presence of internal waves (see Figs. 2 and 3).

From April to August–September the SST increases from \(24^\circ \text{C}\) to more than \(30^\circ \text{C}\), with a temperature increase rate that is larger between April and June and smaller during July and August. By the end of August and early September, the conditions change in a relatively short period of time due to the change of the mean winds and the beginning of the northers season (see Section 3.2.1); the bottom temperature increases rapidly, from \(~22^\circ \text{C}\) in early August to near \(30^\circ \text{C}\) in middle September, and the water column becomes more homogeneous. This suggests that the dominant process causing the homogenization of the water column is downwelling of warm surface water and not mixing, a process that is discussed in Subsection 3.3.1. From October to December, the temperature in the entire column drops from \(~30^\circ \text{C}\) to \(~22^\circ \text{C}\).

### Table 2

Annual minimum, maximum and mean sea surface and bottom temperatures. The month of record is included after the slash. Values from the 24-h running mean time series are included for the bottom temperatures (Temp_24). Mean values at the bottom should be taken with caution since the time series have gaps.

<table>
<thead>
<tr>
<th>Year</th>
<th>SST Min/month</th>
<th>SST Max/month</th>
<th>SST Mean</th>
<th>Bottom Min/month</th>
<th>Bottom Max/month</th>
<th>Bottom Mean</th>
<th>Temp_24 Min/month</th>
<th>Temp_24 Max/month</th>
<th>Temp_24 Mean</th>
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<tbody>
<tr>
<td>2008</td>
<td>22.91/02</td>
<td>30.53/09</td>
<td>26.67</td>
<td>22.27/06</td>
<td>29.25/09</td>
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<td>22.50/02</td>
<td>29.22/09</td>
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<tr>
<td>2009</td>
<td>22.06/12</td>
<td>30.67/08</td>
<td>26.81</td>
<td>21.16/07</td>
<td>29.98/09</td>
<td>24.66</td>
<td>21.56/07</td>
<td>29.89/09</td>
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</tr>
<tr>
<td>2010</td>
<td>19.37/01</td>
<td>30.37/08</td>
<td>25.77</td>
<td>18.72/01</td>
<td>29.45/09</td>
<td>23.50</td>
<td>18.90/01</td>
<td>29.33/09</td>
<td>23.3</td>
</tr>
</tbody>
</table>

**Fig. 3.** Along-coast wind component for the years 2007–2010 at the Veracruz Coral Reef System computed from the NARR: southeastward winds in red and northwestward winds in blue.

#### 3.2. Interannual variability

##### 3.2.1. Winds

It has been shown that the along-coast wind stress component is the main forcing of the dynamics in the inner and middle shelves of the western GoM (Zavala-Hidalgo et al., 2003). Since there are no previous studies analyzing the interannual variability of the winds in the SAV, the along-coast wind component during the years 2007–2010 is reviewed here.
There is an important seasonal variability of the winds, being stronger from September to March when prevailing winds are northwesterlies. Winds are weaker in summer, but with a considerable interannual variability in both direction and intensity (Fig. 3).

In general, during the analyzed period, the norther events lasted longer in September–November than in December–February. In addition, interannual variations in the duration and frequency of norther events were observed; longer duration events occurred during January–February 2007 compared with the other years, when more events of shorter duration occurred.

During the May–July period of 2007 more southeasterly winds were observed compared to that in 2008. On the other hand, in 2009 one strong event of northerly winds occurred in May and a moderate one in July.

### 3.2.2. Temperature

The interannual variability of temperature is analyzed using surface (AVHRR) and bottom (ADCP and thermistor) data for the period 2007–2010, although temperature time series at the bottom have some gaps in the period (Fig. 4). The temperature time series for the years 2007, 2008 and 2010 show a similar vertical structure to that just described for 2009, with almost homogeneous temperatures from middle September to March and water column stratification during spring–summer. Some distinctive features of the interannual variations in the VCRS are described next. In 2008, after the early September bottom temperature rise, there were two events when the bottom temperature decreased, one in the middle of September, of about 5 days, and the other one in November (Fig. 4). However, there is a gap in the time series that does not allow to identify the date when the column became homogeneous again. These re-stratification events are associated with changes in the wind direction pattern, that shows upwelling-favorable winds (northwestward) during these periods (see Fig. 3).

A sudden bottom temperature increase occurred in May 2009 (Figs. 2 and 4), which coincided with a late norther (see Fig. 3) that induced Ekman transport and downwelling. In autumn, a period of water column re-stratification occurred in late September and early October that was associated with northwestward winds (see Figs. 3 and 4). In September 2009, temperatures above 30 °C lasted for several days. Also, the time series show that the 2009–2010 winter was the coldest of the analyzed period.

The bottom temperatures were strongly variable during 2010 compared with the previous three years (Fig. 4). The lowest temperatures of the four years were observed in January 2010, both at the surface and bottom of the water column, being around 3 °C lower than those observed in the previous two years (see Table 2). During spring and summer there were several events in which the stratification was broken that coincided with atmospheric tropical systems, like hurricanes Alex and Karl, that are analyzed in Section 3.3. These systems generated northerly winds over the VCRS, a similar effect to that produced by the northers during autumn–winter (see Fig. 3).

Episodes of high temperatures that may be harmful to the coral reefs were analyzed using 10 min near-surface temperatures from thermistors located at ~1.5 m (surface) and ~5 m depths
during some periods of 2009 and 2010. Observations show that, most of the time, the temperatures at both depths have a difference of less than 0.5 °C (not shown). The frequency distributions of surface temperatures for the period July–October show that, in 2009, more than 79% (35%) of the time they were above 29 °C (30 °C), while during the same period of 2010 they occurred ~44% (12%) of the time (Fig. 5). Considering values greater than 29 °C, the more frequently observed surface temperatures in 2009 were between 29.50 °C and 30.25 °C, while in 2010 they were between 29 °C and 29.25 °C (Fig. 5).

3.3. Intraseasonal variability

In this section, an analysis of the stratification, wind stress forcing and currents during the spring–summer of 2010 is carried out, when several episodes of homogenization of the water column occurred. The currents that are discussed here are those along the direction of maximum variance.

Previous studies have established that winds change direction on a seasonal time scale (Zavala-Hidalgo et al., 2003), being mainly northwestward in late spring and summer and southeastward in autumn–winter, with the occurrence of strong wind events caused by the northers (see Fig. 3). The wind field is analyzed in the VCRS and along the shelf, from the state of Veracruz to the western Campeche Bank (Celestun and Cd. del Carmen). Upwelling favorable winds are observed when the ACWSC is clockwise and downwelling conditions when it is counterclockwise. The western Campeche Bank shows clockwise winds along the year; the TAVE shelf shows clockwise winds in late spring and summer and counterclockwise in autumn–winter, and the Texas–Louisiana shelf has counterclockwise winds most of the year except for small periods in summer, mainly during July (Zavala-Hidalgo et al., 2003). However, high spatial resolution winds from the NARR show a subsection in the TAVE shelf, between Tuxpan and Coatzacoalcos, with weak counterclockwise winds in some periods when most of the TAVE shelf shows clockwise winds (Fig. 6).

This feature has not been reported previously, maybe because it is a local process that seems to be caused by the influence of the Sierra Madre Oriental, which is very close to the shoreline in northern Veracruz. This topographic characteristic develops, in some cases, a southward wind jet that may have different along-coast component than the winds observed 100 km offshore, a pattern that was often observed from middle June to August in 2010. The importance of this feature is that, in some periods, local winds in the VCRS may not be coherent with winds in other sites of the TAVE shelf, as previous studies suggest, making the hydrography and circulation in the VCRS more complex. It should be mentioned that previous studies used wind products with a lower spatial resolution (see Zavala-Hidalgo et al. (2003), Morey et al. (2005)). Also noticeable is the convergence in southern Texas, the relatively small convergence in Coatzacoalcos, and the divergence in Tuxpan, which are observed as large changes in the ACWSC (Fig. 6).

The summer stratification was broken in 2010 due to several tropical storms crossing the Bay of Campeche and to frequent atmospheric low-pressure systems associated with easterly waves. First, hurricane Alex crossed the Gulf of Mexico during June 27–30, breaking the stratification and increasing the bottom temperature from 21.7 °C to 28.7 °C. This event was preceded by a local southward wind in the VCRS, developed as a consequence of an extended atmospheric high-pressure system over the southeastern United States and a relatively low pressure in the northwestern Caribbean (not shown). Later, in early July, an atmospheric low-pressure system offshore of Veracruz favored a stratification reduction, without a complete homogenization of the water column (see Fig. 4).

In the middle of July, a low-pressure system affected the southern Bay of Campeche favoring northerly winds over the VCRS, downwelling conditions and the homogenization of the water column. In late August and early September similar situations were observed. During September 16–18, hurricane Karl again homogenized the water column and, in late September, a norther also broke the stratification. The homogenization observed in August was almost simultaneous with a southeastward current and similar situations were observed related with the events in September. During the last stratification in September, the current remained southeastward, although the local ACWSC barely changed direction on the VCRS, but it did on the Tamaulipas shelf (Fig. 6d).

The contribution of the mixing and inshore Ekman transport in the increase of the bottom temperature is analyzed in the next subsection by means of the ocean heat content changes.

3.3.1. Ocean heat content

In order to better understand the intraseasonal variability of the temperature field, and the events when bottom temperature increases in summer, the ocean heat content of the water column for the period June–September 2010 was estimated from:

$$Q_z = \int_0^z \rho C_p (T(z) - T_0) \, dz,$$

where $\rho$ and $C_p$ are the density and specific heat of sea water, $T$ is the temperature along the water column, and $T_0$ is a constant reference temperature (18 °C in this case) (Fig. 7). This period was chosen due to its significant intraseasonal variability and because it includes the summer to autumn transition. The maximum

![Fig. 5. Percentage of occurrence of sea surface temperatures ≥ 29.0 °C (measured in situ at ~1.5 m) for the period July–October 2009 (left) and 2010 (right).](image-url)
increase of heat content occurred at the end of June, followed three days later by a decrease of the same magnitude and a re-stratification of the water column (see Figs. 4 and 7). Another two increases occurred in July, one having around half of the magnitude of that occurred in June and the other one reaching a similar magnitude. In early August, the heat content increased again, remaining moderate for more than 15 days. Later, during the last third of August, the heat content increased again, remaining high until early September when the largest value was reached (Fig. 7). Note that the re-stratification periods that occurred in autumn...
3.4.1. Temperature inversions

In order to better visualize the temperature inversions, sections for January 13 and March 15, 2010 are presented in Fig. 10 using an appropriate temperature scale. In these sections the 2009 and 2010 coincided with periods of southeasterly winds (see Fig. 3). The heat content time series shows that during events when the bottom temperature rises, the heat content has a significant increase, which supports the hypothesis that the dominant process causing the bottom temperature increase is downwelling. If mixing were the dominant process the heat content would not increase.

Since it appears that inshore Ekman transport may be the cause of the ocean heat content increase, the correlations of the surface–bottom temperature difference with the currents and with the along-coast wind stress component were computed for the period June–August 2010, when stratification shows large changes. To compute the correlations, the variables were normalized and a 48-h running mean filter applied (Fig. 8), which is slightly larger than the inertial frequency. The correlation with the wind stress component along the coast was 0.48 for a lag of 1.8 days, and with the along-coast currents was 0.67 for a lag of 1.6 days. These results imply that stratification (homogenization) is observed with upwelling (downwelling) favorable winds and northwestward (southeastward) currents.

Another result from the computation of heat content is that, on average, the ocean heat content is larger in September than in June–August, although the surface heat flux in the gulf is positive during June–August and near zero in September (Zavala-Hidalgo et al., 2002).

3.4. Thermohaline structure

Eleven CTD surveys were carried out between 2006 and 2010, covering all seasons. Data were collected along sections perpendicular to the coast, from the shoreline to around 10 km offshore, approximately up to the 45 m isobath (see Fig. 1 for location of sections). Data of the 2010 surveys were chosen as representative of the seasonal thermohaline structure and examples for winter, spring, summer and fall are analyzed (Fig. 9).

Results show an important variability of the thermohaline structure along the year. In winter, the water column is nearly vertically homogeneous, with low temperature (< 20.5 °C) and low salinity (< 35.25 psu) waters (Fig. 9, upper panels). These waters have a relative deep penetration (> 40 m), suggesting that they may come from the northwestern shelves of the gulf. This is consistent with observations on the Texas–Louisiana shelf by Li et al. (1997) who, based on 5 surveys carried out during November, reported salinities of less than 30 ups and temperatures of less than 21 °C. Also, studies based on drifters (Morey et al., 2003; Ohlmann and Niiler, 2005; DiMarco et al., 2005) and numerical simulations (Zavala-Hidalgo et al., 2003) show water displacement from the Texas–Louisiana shelf toward the shelf of Veracruz. The deep penetration of low salinity water during autumn–winter is consistent with the idea of the influence of remote discharges (as far as the Mississippi and the Texas rivers), high mixing and downwelling conditions.

Associated with the winter structure mentioned above, the Brunt–Väisälä frequency ($N^2$, $N = \sqrt{(-g/\rho) (d\rho/dz)}$, as a measure of stratification, shows very low values (Fig. 9). During this season, some temperature inversions were observed and they are discussed in Subsection 3.4.1.

The water column begins to stratify in spring, showing a thin layer (0–5 m) of warm (~27.5 °C) and medium salinity (~35.5 psu) waters above colder and saltier waters. The stratification is present in the upper 15 m, as shown by the larger values of $N^2$ (Fig. 9, middle upper panels).

During summer, the water column is strongly stratified, with very warm (>28 °C) waters in the first 20 m that drops to ~22 °C at ~40 m depth. A thin upper layer, of less than 6 m depth, with salinity lower than 34 psu was observed as a consequence of local rivers discharge, which peaks in this season. Very large values of $N^2$ are shown mainly within this upper fresher layer and at the depth of the thermocline (Fig. 9, middle bottom panels). In this season, upwelling-favorable winds prevail.

In autumn, when the northers season begins, strong downwelling favorable winds and mixing cause the homogenization of the water column, showing low salinities (<35.5 ups) and almost the same temperature (~27.5 °C) from surface to bottom. A very low salinity surface layer was observed, associated with the largest values of $N^2$ (Fig. 9, bottom panels).
inversions reached more than 1.5 °C and 0.5 °C, respectively. To analyze the frequency of temperature inversions, the thermistor records at 5 m and 27 m depths in 2009 and 2010 were used. The occurrence of an event is considered when the difference between bottom and surface temperatures is positive. All of the temperature inversions were observed between September and March and a summary is presented in Table 3. The resulting values show that there were more events in 2009 (18) compared to those observed in 2010 (13) but, on average, they lasted slightly longer and were stronger in the latter year. From a detailed review of the conditions that were present when these events happened, like a preferred time of occurrence, the coincidence with an atmospheric norther or the association with northward or southward currents, we could not find any pattern except that inversions occurred during autumn–winter. It is possible that they were associated with internal waves, but our data are not enough to corroborate it.

Table 3

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of events</th>
<th>Mean duration (days)</th>
<th>Mean difference (°C)</th>
<th>Mean of the maximum difference (°C)</th>
<th>Absolute maximum difference (°C)</th>
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<td>13</td>
<td>1.99</td>
<td>0.29</td>
<td>0.53</td>
<td>1.73</td>
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</table>
3.5. Temperature–salinity analysis

A characterization of the temperature–salinity features of the waters in the VCRS and its seasonal variability is carried out based on the profiles of the eleven CTD surveys. The data were grouped by season as follows: Winter (3 surveys), Spring (2 surveys), Summer (5 surveys), and Fall (one survey) (see Table 1 for dates).

The T/S diagram of all the oceanographic surveys shows the presence of the Gulf Common Water (GCW) in the VCRS, characterized by a salinity of 36.5 psu and temperatures between 21.2 °C and 30.0 °C (Fig. 11). The diagram also shows the influence of fresh and warm waters from regional rivers in summer and the presence of water with relatively low salinity and temperature in winter that comes from the shelves in the northwestern gulf, which is consistent with observations by Li et al. (1997).

During spring and summer, the GCW usually mix with upper-layer waters characterized by lower salinities and higher temperatures. In these seasons, the salinity increases with depth almost continuously and the temperature decreases. In autumn, the water column is almost homogeneous with warm temperature and relatively low salinity.

Temperature inversions were observed in the winter surveys of January and March 2010 (see Fig. 10), which can be inferred from the T/S diagram since denser waters have higher temperatures than lighter waters at the surface (isopycnals in the diagram are useful to identify denser or lighter waters). In January 2010, as mentioned before, the salinity did not reach 36.0 psu suggesting that the temperature inversion reaches depths greater than 45 m, the maximum surveyed depth.

4. Final remarks

A well defined seasonal cycle was identified in the VCRS, with stratification and upwelling favorable winds from May to August and an homogeneous water column associated with downwelling and mixing conditions from September to March. April is a transition month. A stratified water column is semi-permanent during late spring and summer, even in cases when the winds and currents change direction locally.

The annual cycle of temperature was similar in the four years of observations, although with some interannual variations. The lower bottom temperatures of the 2007–2010 period occurred in early 2010, reaching 18.7 °C, which were between 3 °C to 4 °C below the temperatures observed in the previous years. Atmospheric tropical systems that affected the VCRS during 2010 generated northerly winds that changed the prevalent upwelling summer conditions into temporal downwelling patterns and broke the stratification. These events caused an increase of the bottom temperature of around 5 °C, to reach ~29 °C, and an increase in the water column heat content. This kind of events were not observed during 2008 and 2009.

The higher SSTs were observed between July and early October, being frequently above 30 °C and reaching more than 31 °C in several occasions. Between July and October of 2009 the number of days with temperatures above 30 °C was considerably larger than in 2010. At the bottom, at 30 m depth, the higher temperatures were observed in September, when the wind pattern changed and the northers season began, changing the upwelling summer conditions into downwelling patterns. The main process involved in this temperature rise is downwelling and not mixing, since the vertically integrated ocean heat content increases.

The GCW is observed in the VCRS. Also, water with low salinity near the surface due to the influence of local rivers discharge during summer, and the cold, low salinity water advected from the northwestern shelves of the Gulf of Mexico during autumn–winter are present.

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