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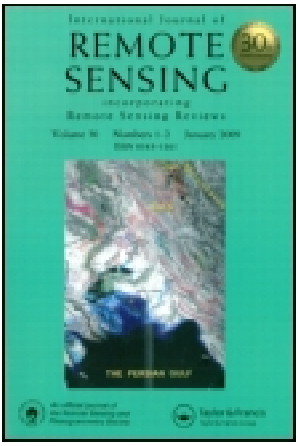

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Evaluation of the MODIS-Aqua Sea-Surface Temperature product in the inner and mid-shelves of southwest Buenos Aires Province, Argentina

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Validation of sea-surface temperature (SST) provided by the MODIS-Aqua sensor (Moderate Resolution Imaging Spectroradiometer) for the inner and mid-shelves of the southwest of Buenos Aires Province (Argentina), is presented for the first time. *In situ* data obtained with a multi-parametric sonde YSI-6600 and a CTD SBE91 between 2002 and 2011 are used for comparison with the satellite SST product. The match-up exercise was established after comparing different spatial boxes, time difference windows, wind speeds, and also a coefficient of variation. The comparison exercise was made in the coastal zone and the rest of the inner and mid-shelves separately. In the coastal zone, applying a 3 × 2 pixel box and a time window of ±3 hours led to the most accurate results, with a coefficient of determination (R^2) of 0.99, a bias of 0.62°C, and a root-mean-square-error (RMSE) of 0.79°C. In the inner-mid-shelves when applying a coefficient of variability <0.3, a time window of ±3 hours, and taking only values of wind speed > 6 m s^{-1}, R^2 is 0.97, bias is 0.46°C, and RMSE is 0.95°C. Wind speed plays a major role in the inner-mid-shelves as the SST product is affected by stratification and formation of a diurnal thermocline in the 'skin and sub-skin layer' when wind speed is below 6 m s^{-1}. The results for the two shelves are very similar. Finally, the spatial and temporal variability of the SST satellite product was analysed in the study area for the period August 2002–December 2010. The results show that inter-annual variability is not significant and that there is no positive or negative trend for the 9 years of the study. Seasonality is the main component of temporal variability, with variation in amplitude signal depending on bathymetry changes, physical forcing, stability of the water column, and presence of flood plains.

1. Introduction

The inner mid-shelf of southwest Buenos Aires Province (Argentina, Figure 1) is characterized by large inputs of continental run-offs, locally generating cells of high salinity and winds which dominate the inner-shelf dynamics (Piccolo 1998; Lucas et al. 2005). In addition, the coastal zone of Buenos Aires Province presents a semi-annual cycle front with its highest intensities in winter (June) and spring (November), due to the marked transfer of heat from coastal waters towards the atmosphere and *vice versa* (Rivas and Pisoni 2010). In the mid-shelf there is a thermal front (from 50 m isobath offshore) that separates well-mixed nitrate rich coastal waters from the seasonal stratified mid-shelf waters, which becomes stronger in spring (Romero et al. 2006). The highly diverse

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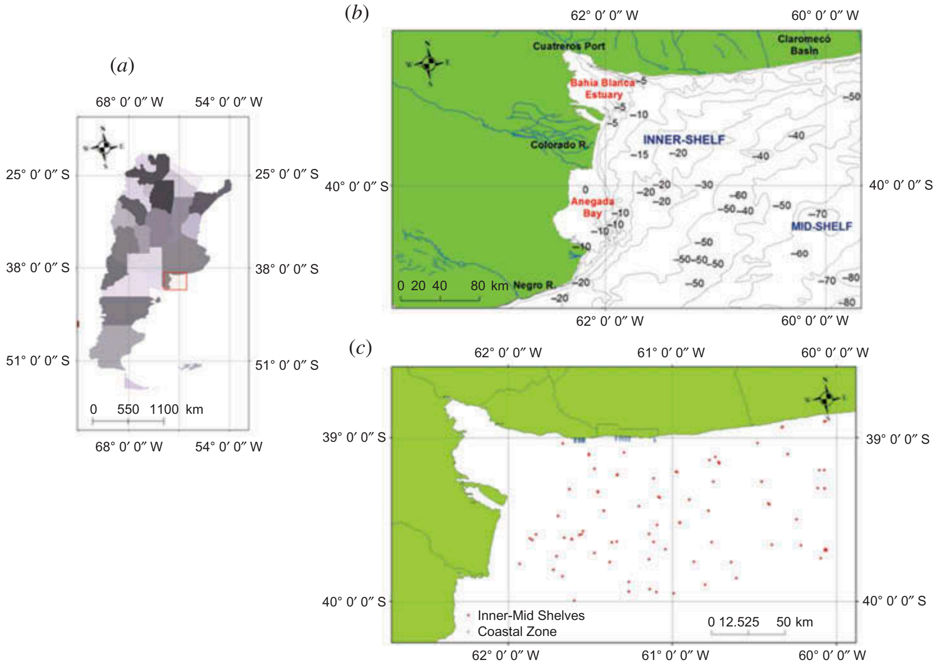

Figure 1. Location of the study area and the *in situ* stations. (*a*) Map of Argentina; (*b*) study area; (*c*) location of *in situ* measurements: blue points make reference to coastal measurements and red points to inner mid-shelf stations.

physical and biological characteristics generate a rich habitat of valuable species, which are very important for the local fisheries (Carroza, Fernández Aráoz, and Pájaro 2009). To understand the functioning of this complex ecosystem it is fundamental to know the dynamics of physical parameters, such as sea-surface temperature (SST). Unfortunately, the lack of economical resources in South America is a limitation to obtaining bulk measurements or to developing autonomous observatories.

Sea-surface temperature is one of the most important parameters used to define the physical environment and the variability of marine ecosystems (Lee et al. 2005; Hosoda et al. 2007), and it is considered as an Essential Climate Variable. SST gradient fields are used as a proxy to define marine thermal fronts, which are water masses with optimal conditions for growth of marine phytoplankton (nutrients, light, mixing, and upwelling) and in many cases enhance high trophic level productivity (Le Fèvre 1986; Largier 1993; Acha et al. 2004; Saraceno and Provost 2005; Rivas and Pisoni 2010). The spatial and temporal patterns of SST are one of the most important characteristics of fisheries ecosystems, having implications for their sustainable management (Santos 2000; Williams et al. 2010, 2013). On the other hand, SST has a major impact on the gas exchanges between the ocean and the atmosphere, as well as on energy exchanges such as fluxes of sensible heat, latent heat, and long-wave radiation (Barton 2001; Lee et al. 2005; Barton and Pearce 2006). It is also a fundamental parameter of numerical models of oceanography, marine weather, and climate (Barton and Pearce 2006; Hosoda et al. 2007).

A very useful tool for global study of SST is to use satellite data. This method allows acquisition of data over high spatial and temporal resolution all over the globe. Remote sensing of SST started in 1981 with the launch of the Advanced Very High Resolution

Radiometer (AVHRR) sensor on board the NOAA (National Oceanic and Atmospheric Administration) satellite, and it is still operational. Since May 2002, the Moderate Resolution Imaging Spectoradiometer (MODIS) on board the Aqua platform (NASA) has provided worldwide daily coverage of SST at 1 km resolution. MODIS is considered to obtain clear SST fields and to present more accurate results than AVHRR (Hosoda et al. 2007; Lee et al. 2010).

To confirm satellite data it is necessary to validate the results with *in situ* SST measurements. Many studies have been made on validation of the MODIS SST product in global and coastal oceans, showing good accuracy (e.g. Minnet et al. 2002; Barton and Pierce 2006; Hosoda et al. 2007; Lee et al. 2010; Hosoda and Qin 2011). In Argentina, MODIS SST data were validated for the inner shelf of La Plata River (Simonato et al. 2010) and in the San Matías Gulf (Williams et al. 2013), showing accurate retrieval. However, no validation of the MODIS Aqua SST product in the inner and mid-shelves of southwest Buenos Aires Province has been conducted to date.

In the present study, the validation of MODIS SST at 1 km resolution is presented for the first time for the inner and mid-shelves of southwest Buenos Aires Province with *in situ* data obtained between 2002 and 2011. In addition, SST temporal and spatial variability is studied.

2. Materials and methods

2.1. In situ *and satellite data*

The *in situ* sea-surface temperature data were obtained from two different sources. In the coastal zone (Figure 1), SST was measured at the surface layer (1.5–13 m) between March 2010 and February 2011 at 43 stations, giving to a total of 266 measurements (Figure 1, Table 1). The SST was obtained with the multi-parametric sonde YSI-6600, which measures at a frequency of 1 s. The sonde has a thermistor of sintered metallic oxide that detects temperature variation at an accuracy of 0.1°C. The quality of the data was manually controlled to avoid any spikes or duplicates. In addition, the data were compared to the expected ranges of temperature based on previous research in the study area or nearby (monthly, seasonally, and climatologically) (Martos and Piccolo 1988; Piccolo 1998; Perillo and Piccolo 1999; Cuadrado, Piccolo, and Perillo. 2002; Lucas et al. 2005). Also, every datum was compared to data taken from stations less distant (500–1000 m) in order to prove their consistency.

Table 1. Number of *in situ* measurements by month in the coastal zone and inner mid-shelves.

Coastal zone		Inner mid-shelves	
Month	No. of measurements	Month	No. of measurements
March 2010	34	March 2002	52
April 2010	14	November 2002	8
May 2010	25	November 2003	9
July 2010	35	August 2004	30
September 2010	34	October 2004	10
October 2010	31	December 2004	30
November 2010	30	December 2005	35
January 2011	35	November 2006	10
February 2011	28	November 2008	43
Total	266	Total	227

The inner and mid-shelf data were provided by the Base Regional de Datos Oceanográficos (BaRDO, Regional Base of Oceanografic Data), which is dependent on the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP) (Baldoni and Molinari 2008). Nine oceanographic campaigns were undertaken between 2002 and 2008, for a total of 227 measurements of SST with a CTD SBE91 (Figure 1, Table 1). The measured temperature is the mean of measurements taken between the surface and a depth of 5 m, with an accuracy of 0.003°C. The data provided were evaluated with quality controls which rely on international standards of the IOC (International Oceanographic Commission), the IODE (International Oceanographic Data and Information Exchange), and the GETADE (Group of Experts on Technical Aspects of Data Exchange). The quality controls (QCs) are grouped thus: QC0, data concerning the location of the station data (e.g. boat speed, regional and global ranges, duplicates); QC1, data of the profile (e.g. global ranges, spikes, gradients); and finally QC2, the consistency of the data in relation to the known climatological conditions (monthly, seasonally, and annually) of the World Ocean Atlas 2001 (WOA01) Ocean Climate Laboratory – National Oceanographic Data Center (OCL-NODC (Baldoni and Molinari 2008; Baldoni et al. 2008; Boldoni et al. 2008).

The SST satellite data were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board Aqua. The Ocean Biology Processing Group (OBPG) from NASA generates the Level 2 SST product, retrieved from the infrared bands using the non-linear sea-surface temperature (NLSST) algorithm (Brown and Minnet 1999). Daily products at 1 km resolution from 2002 to 2011 were downloaded from the OceanColor web site (http://oceancolor.gsfc.nasa.gov). L3 monthly products were obtained from the daily L2 SST, in order to analyse the spatial and temporal distribution of the variable in the study area, in MERCATOR projection.

Wind satellite data were obtained from the SeaWinds scatterometer on board QuikSCAT. The sensor is a microwave radar that measures near-surface wind speed and direction (http://winds.jpl.nasa.gov). Daily products of 0.25° of spatial resolution were downloaded for the days corresponding to the *in situ* measurements from the webpage of Remote Sensing Systems (http://www.ssmi.com/).

2.2. Match-up protocol

Because the SST *in situ* data were obtained from two different areas and also from different instruments, the validation was made separately. The match-up procedure consists in extracting a box of 3 × 3 (inner mid-shelves) or 3 × 2 pixels (near-coastal zone), centred on the location of the *in situ* measurements. The use of a multi-pixel box allows the calculation of the mean and standard deviation of SST to investigate the spatial homogeneity over the box at the validation point (Bailey and Werdell 2006). In a first step, for the coastal zone, the size of the box was 3 × 3 pixels. Since the area is located approximately 2.5 km off the coast of Buenos Aires Province, a 2 × 3 pixel box was applied in order to limit the effect of the land on the match-up satellite data (Jamet et al. 2011). In the case of the inner mid-shelf data, a 3 × 3 pixel box was applied. A match-up is accepted only if all pixels of the box are valid (nine for the 3 × 3 box and six for the 3 × 2 box) (Bailey and Werdell 2006; Jamet et al. 2011). Then, a spatial uniformity criterion is applied based on the coefficient of variation (CV), defined as the ratio of the standard deviation to the mean pixel value of the satellite box. A match-up is accepted when the coefficient of variation is <0.3 (Bailey and Werdell 2006). In addition, a manual quality control procedure is done, removing all pixels found in cloud borders. This consists in checking on satellite images that the match-ups are not located in cloud borders, in order to avoid failures in validation results because they do not allow real SST to be obtained.

To obtain the most representative SST, the time difference between satellite overpass and *in situ* measurement was taken into account. A time difference of ±24 or ±3 hours was studied for the two zones (Barton and Pierce 2006; Hosoda et al. 2007; Lee et al. 2010). In addition, as wind speed is one of the main factors in the stratification of the upper ocean layer, the accuracy of the SST satellite product is also verified as a function of wind speed (wind speed > 6 m s^{-1} = no stratified upper layer, <6 m s^{-1} = stratified upper layer) (Donlon et al. 2002).

2.3. Statistical analysis of the validation

In order to evaluate the performance of the MODIS-Aqua SST algorithm, a statistical analysis was performed comparing the *in situ* data to the satellite data. At first, a linear regression was carried out and the slope, intercept, and coefficient of determination (R^2) were compared. The statistical parameters used for the evaluation were root-mean-square-error (RMSE) (Equation (1)), bias (Equation (2)), relative error (RE) (Equation (3)), and standard deviation (sd) between the *in situ* measurements and satellite data. The parameters are defined as:

$$\mathrm{RMSE} = \sqrt{\left(\sum\left(\frac{x_m - x_{in}}{x_{in}}\right)^2 \frac{n}{1}\right)}, \tag{1}$$

$$X(t) = S(t) + T(t) + I(t), \tag{2}$$

$$\mathrm{RE} = \left(\sum\left(\sqrt{\left(\frac{x_{in} - x_m}{x_{in}}\right)^2}\right)\right)\frac{n}{1}, \tag{3}$$

where $\overline{x_m}$ is the satellite data, $\overline{x_{in}}$ is the *in situ* data, and n the number of match-ups.

2.4. Statistical analysis of the temporal and spatial variability of SST

SST monthly means for the period August 2002–December 2010 were computed from daily data and analysed in order to define the spatial and seasonal climatology behaviour of the SST in the study area. These monthly time series were decomposed using the Census X-11 method, whose application to time-series analysis of SST data (Pezzulli, Stephenson, and Hannachi 2005) and on oceans has been extensively documented (Vantrepotte and Mélin 2009; Vantrepotte et al. 2011; Vantrepotte and Mélin 2011). In practice, this method aims at decomposing a time series $X(t)$ (here, monthly L3 products) into three additive components:

$$X(t) = S(t) + T(t) + I(t), \tag{4}$$

where S is the seasonal signal, T the trend cycle signal, and I the irregular or residual signal (Shiskin 1978; Vantrepotte and Mélin 2009).

The detailed CensusX11 is documented in Vantrepotte and Mélin (2011). Briefly, it is based on an interative bandpass filtering procedure, the major interest of which is to allow for the definition of a non-periodical seasonal term thus allowing specific assessment of year-to-year variation in time-series seasonality (in terms of period and amplitude). To identify the spatial patterns of the temporal variability in the series, the relative part of the variance of the components is estimated for each grid point. In addition, the presence of significant monotonic long-term change in the time series was evaluated using the non-parametric seasonal Kendall statistics, while the amplitude of the changes was evaluated by the non-parametric Sen's slope estimator expressed as % year^{-1} (Gilbert 1987; Vantrepotte et al. 2011).

3. Results

3.1. Validation of SST product

3.1.1. The coastal zone

In the coastal zone (Figure 1), the match-up exercise was done using a 3 × 2 pixel box and a ±3 hour time difference window. The coefficient of variation (CV) was applied but in this case all results showed a value lower than 0.3. This means that the MODIS retrievals did not show high variability inside the 2 × 3 pixel box. On all measurement days, low wind conditions prevailed (<6 m s^{-1}), which are not the most representative conditions, as the mean wind speed in this area is 6.19 m s^{-1} (SMN 1992).

Figure 2 presents a comparison of the match-up analysis using different time windows. It shows that the retrievals of SST are close to the 1:1 line whatever value of the time difference is taken, especially for the low values of SST. The scatter of the data around the 1:1 line increases with the increase in SST values (Figure 2(*a*)).

Using a 3 × 2 pixel box (Figure 2(*a*)) with a time difference of ±24 hours led to 79 match-ups from the original dataset (266) (Table 2). In statistical terms, the results were accurate, presenting an R^2 of 0.97, RMSE of 1.17°C, and bias of 0.74°C.

Applying the time difference window of ±3 hours to the 2 × 3 box led to 28 match-ups. The decrease in match-ups corresponds to the remove of SST values above 20°C. The SST retrieval showed higher accuracy with this smaller time window, with a R^2 of

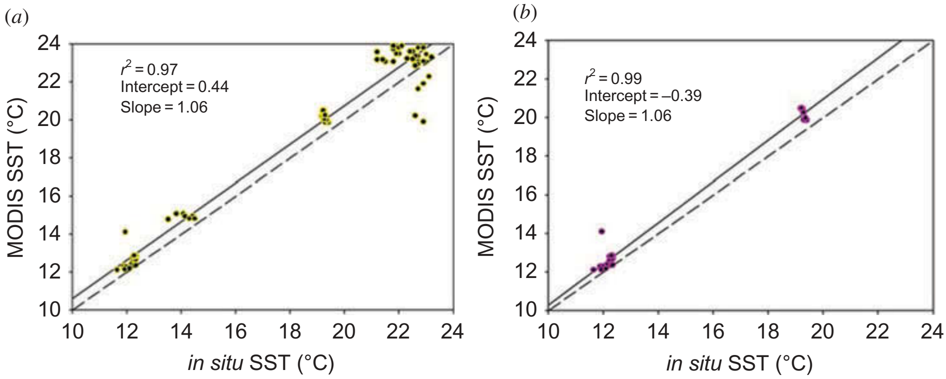

Figure 2. Scatter plots of the *in situ* data in the coastal zone with Aqua MODIS SST: (*a*) with the extraction box of 3 × 2 pixels and (*b*) with the extraction box of 3 × 2 pixels and the time difference window of ±3 hours.

Table 2. Statistical results of validation of SST Aqua MODIS product for the coastal zone and inner mid-shelves.

	Coastal zone		Inner mid-shelves					
	No CV		No CV		CV < 0.3			
	±24 hours	±3 hours	±24 hours	±3 hours	±24 hours	±3 hours		
Statistics						Total	$W < 6$ m s^{-1}	$W > 6$ m s^{-1}
Number of match-ups	79	28	99	28	81	21	14	7
Bias (°C)	0.74	0.62	–0.58	–0.14	0.47	0.70	0.59	0.46
RMSE (°C)	1.17	0.79	2.70	2.62	1.11	1.39	1.43	0.95
Correlation	0.97	0.99	0.72	0.95	0.95	0.95	0.95	0.97
SD (°C)	0.90	0.49	2.64	2.67	1.01	1.22	1.35	0.90
R error (%)	4	3	18	19	6	7	91	3

Note: SD, standard deviation; R error, relative error; *W*, wind speed; CV, coefficient of variability; No CV, the CV was not applied.

0.99, bias of 0.62°C, and RMSE of 0.79°C (Figure 2(*b*)). In addition, the plot is less scattered than with the time difference of 24 hours. It is possible to see, in comparing Figures 2(*a*) and (*b*), that the match-ups which were eliminated were those with more dispersion, corresponding to summer data (21–23°C).

3.1.2. *Inner and mid-shelves*

The validation of SST data for the remainder of the inner and mid-shelves was made with a 3 × 3 pixel box, and the results for the match-ups performed in these shelves are presented in Figure 3 and Table 2. In regard to the coastal zone, applying different filters improved the accuracy of the SST retrievals. Figure 3(*a*) presents the match-up results with no constrains on time difference, CV, or wind speed. The MODIS-Aqua SST showed high scattering around the 1:1 line, mainly between 13°C and 16°C. The slope of the regression line was 0.88 and intercept in 0.94. In statistical terms, R^2 was 0.72, bias was 0.58°C, and RMSE was 2.7°C (Table 2). The number of match-ups was high (99), though the results were the least accurate of all analyses.

Applying only the CV, the retrievals led to a decrease in scattering around the 1:1 line, with a slope of 0.96 (Figure 3(*b*)). The number of match-ups eliminated with this filter was 11, giving a total of 88 results with correlation of 0.95, positive bias of 0.47°C, and RMSE of 1.1°C. Applying only the time difference window (±3 hours) led also to a decrease in scattering, with the slope of the regression line being closer to the 1:1 line (1.01) (Figure 3(*c*)). However, the number of match-ups greatly decreased to 28, as well as the bias and RMSE (–0.14 and 2.62, respectively), while R^2 increased to 0.95 (Table 2). With the combination of both constraints (3 hour window and CV, Figure 3(*d*)), the statistical results did not improve as R^2 was still 0.95 but the number of match-ups decreased from 88 to 21 and the bias and RMSE increased to 0.7°C and 1.39°C, respectively (Figure 3(*d*) – Table 2). These results are similar to those obtained with a ±3 hour time window (Figure 3(*c*)).

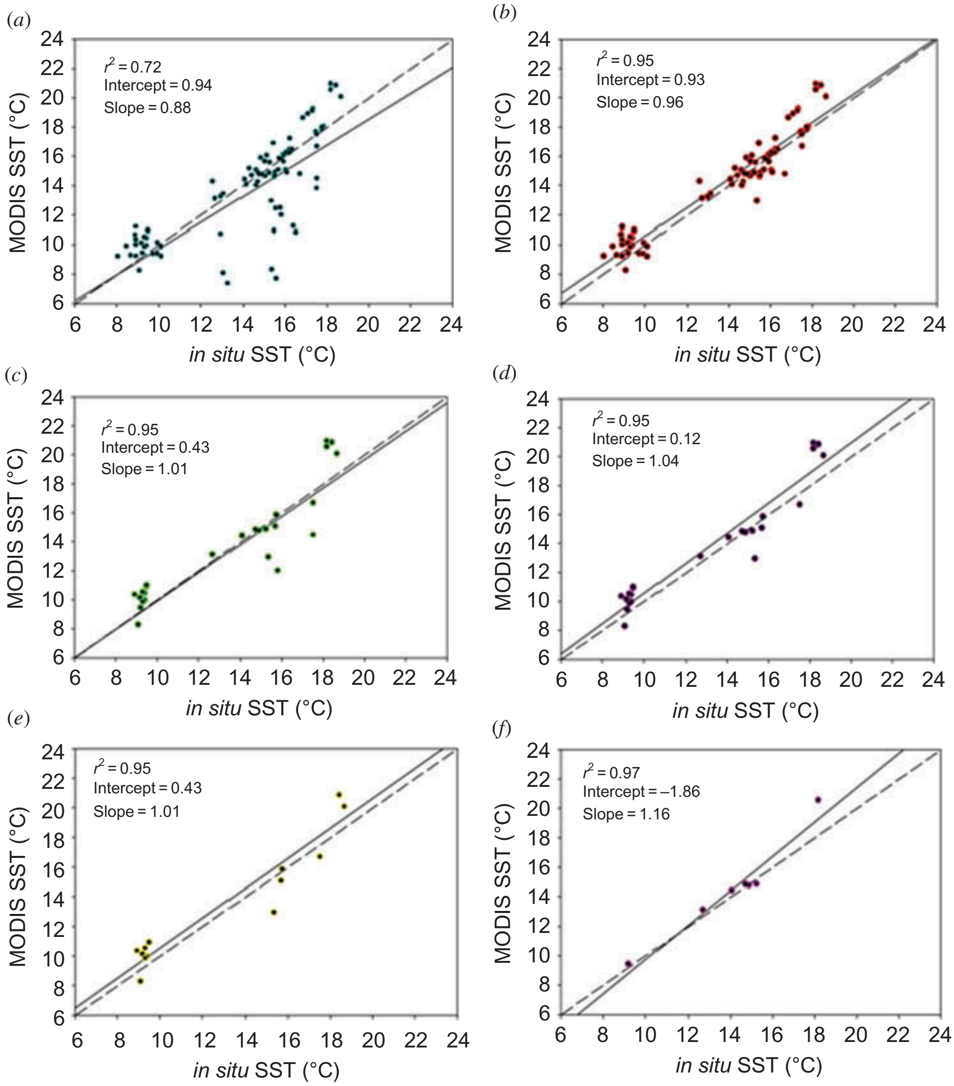

Figure 3. Scatter plots of the *in situ* data in the inner and mid-shelves with Aqua MODIS SST applying the extraction box of 3 × 3 pixels: (*a*) with no constraints; (*b*) applying the CV; (*c*) applying the time difference of ±3 hours; (*d*) with the CV and the time difference window of ±3 hours; (*e*) with the CV, time difference window of ±3 hours, and wind speed of <6 m s^{-1}; and (*f*) with the CV, time difference window of ±3 hours, and wind speed of >6 m s^{-1}.

Finally, wind speed was taken into account. When wind speed in the study area was over 6 m s^{-1}, the satellite data were more accurate, presenting the highest R^2 of the results in the inner mid-shelves (0.97) (Figure 3(*f*)). The bias was 0.46°C and the RMSE 0.95°C (Table 2). Meanwhile, under low wind conditions (<6 m s^{-1}) the bias was 0.59°C and the RMSE was 1.43°C. This is explained by the fact that high wind speed produced a vertical wind-driven mixing, avoiding overheating of the upper layer of the water (Barton and Pearce 2006).

3.2. Spatial and temporal analysis of SST variability

Monthly climatological analysis shows that SST distribution in summer (January–March) ranges between approximately 15°C and 23°C in the study area (Figure 4). The coastal zone outside Bahía Blanca estuary and Anegada Bay presents maximum temperatures (23–25°C in January) while in the rest of the coast and inner shelf, SST ranges between 19°C and 23°C. The mid-shelf has a completely different range of mean temperatures (15–16°C). In autumn (April–June), SST ranges between 10°C and 17°C over the entire study area (Figure 4). It is noticeable how the interaction between coastal waters, where the slope of the bottom is very shallow (flood plains, Figure 1(*b*)), and the atmosphere leads to a significant cooling effect (Beigt, Piccolo, and Perillo 2003; Piccolo 2009). For example, in the coastal area of Bahia Blanca estuary, SST reaches 11–13°C. The mid-shelf presents approximately the same range of temperature, which is explained by stratification of the water column: as air temperature decreases the upper layer cools down, while the layers beyond remain warmer. The inner shelf is the warmest zone in autumn (15–18°C) (Figure 4). The sea–air dependency on SST bias can be clearly observed in maps of sea–air temperature difference on the following website: http://www.star.nesdis.noaa.gov/sod/sst/micros. In spring and summer, the sea–air temperature difference is –4 K (August–November), which causes a warming effect on the sea, while in autumn/winter, the temperature difference is positive with the maximum difference in June (4 K). Between December and April the sea–air temperature differences are smaller, ranging between 0 and ±3 K.

Outside the tidal flats of Bahia Blanca estuary (Figure 1(*b*)), SST reaches 7°C in winter (July). Similar values were found at the mouth of the estuary and in Anegada Bay (8°C), where SST in the mid-shelf was approximately 8–10°C. In July, SST in the inner shelf is about 12–13°C. Warmer SST can be explained by the warm, salty current from San Matías Gulf, typically in winter (Guerrero and Piola 1997; Lucas et al. 2005). The San Matías Gulf current dissipates by the end of winter, and water temperature begins to increase in spring from the very coastal areas towards the outer shelf. A higher SST was found outside tidal flats (16°C), while the rest of the inner shelf had an SST around 11°C.

The outputs of Census X-11 time series decomposition procedures showed that the seasonal signal ($S(t)$) dominates the temporal variability in SST (>95%), while the trend ($T(t)$) and irregular ($I(t)$) variations were not significant. Further, the linear trend test applied to SST data also demonstrates the absence of significant change over the period investigated. A clear homogeneity of the latter features (ultra-dominance of seasonal oscillation and absence of significant trend) was observed over the area investigated without marked spatial patterns (not shown). Considering these latter results, further investigation will specifically focus on the amplitude of seasonal variation.

Three regions of interest were chosen, one in the coastal zone between Anegada Bay and Bahia Blanca estuary, one in the inner shelf, and the third in the mid-shelf (Figure 5(*a*)). All three regions show the same temporal behaviour, though signal amplitude varied depending on the area. The coastal zone had the highest amplitude, ranging from –7°C (winter 2010) to +8°C (summer 2005), leading to a maximum amplitude of 15°C for the 9-year period. The lowest amplitude was found in 2007, at 12°C (Figure 5(*b*)). The amplitude of the seasonal component is less in the region located in the inner shelf (11°C), with a maximum value of +6°C in 2005, 2009, and 2010 and a minimum of –8°C in 2007, like the coastal zone (Figure 5(*c*)). Finally, the mid-shelf presented the lowest amplitude of the entire area, with a value of 10°C, with the lowest value of the signal in winter 2010 (–4°C) and the highest in summer 2009 (+6°C) (Figure 5(*d*)).

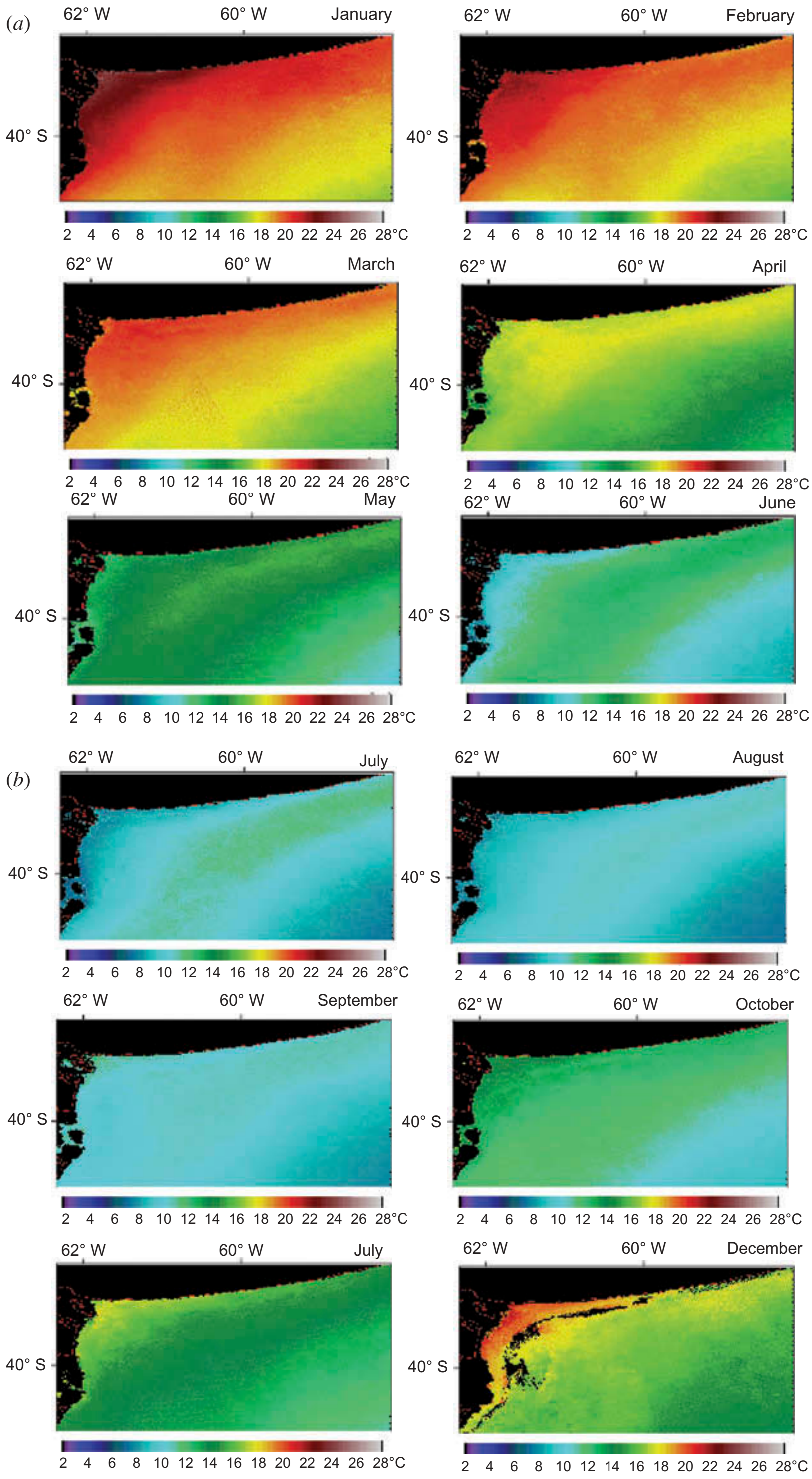

Figure 4. Aqua MODIS monthly L3 mean products at 1 km resolution for January–June (*a*) and July–December (*b*) for the period August 2002–December 2010 in the southwest inner mid-shelves of Buenos Aires Province, Argentina.

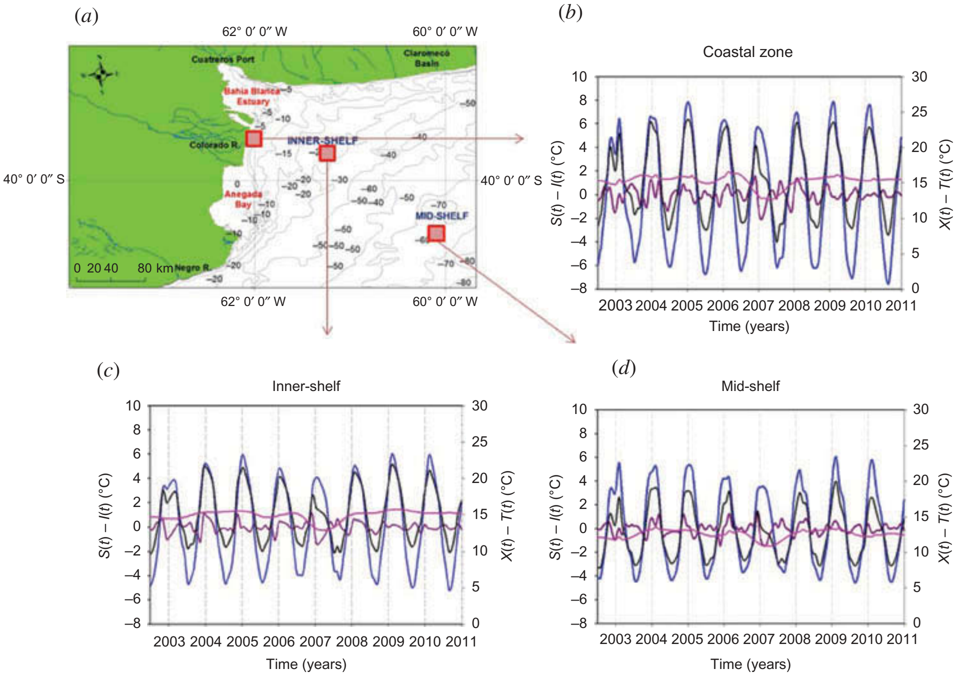

Figure 5. Detailed analysis of regions of interest with Census X-11 results. (*a*) Location of the study area with the three sub-zones; (*b*) coastal zone; (*c*) inner shelf region; and (*d*) mid-shelf region. The black line represents the total signal of variability ($X(t)$), the pink line is the trend component ($T(t)$), the blue line is the seasonal component ($S(t)$), and the purple line is the irregular component ($I(t)$). The left-hand axis represents the $S(t)$ and $I(t)$ components, and the right-hand axis the $X(t)$ and $T(t)$ signals (°C).

4. Discussion and conclusions

In this study, we present the first validation of the SST MODIS-Aqua product in the coastal zone and inner mid-shelves of south-west Buenos Aires Province, Argentina, using *in situ* data. In addition, statistical analysis was performed based on satellite data in order to determine the seasonal and spatial behaviour of SST as well as its inter-annual variability for the period 2002–2010.

For validation, more accurate results were obtained when the coefficient of variation, a short time difference window, and wind speed were combined. In the coastal zone, applying a 3 × 2 pixel box and a ±3-hour time window led to a coefficient of correlation of 0.99, bias of 0.62°C, an RMSE of 0.79°C. In the inner and mid-shelves the best results were obtained using a CV, a 3 hour time window and wind speed > 6 m s^{-1}, leading to R^2 of 0.97, bias of 0.46°C, and RMSE of 0.95°C. In this area, applying a CV was critical as it eliminated the highly scattered match-ups. The high CV values were due to match-ups located in cloud borders, where some pixels were not flagged.

SST satellite retrievals are very sensitive to the thin skin layer surface since it can be reheated during the day, affecting the final results (Gentemann et al. 2003). Many studies have addressed the issue that the amplitude of SST diurnal variation caused by solar heating can reach and sometimes exceed 3 K, especially in summer with blue skies and calm days in the mid-latitudes (Stramma et al. 1986; Price et al. 1987; Yokoyama, Tanba, and Souma 1995; Fairall et al. 1996; Kawai and Kawamura 2002). In this sense, our *in* *situ* data were taken during the daytime, so this could be one of the reasons for the differences found between satellite and the field data. The time window is effective in partially eliminating the diurnal heating effect suffered by the skin layer. This phenomenon is suggested to be very intensive in the very coastal waters of Buenos Aires Province, mainly in summer when the data showed more dispersion.

Furthermore, all the coastal and most of the inner and mid-shelf measurements were taken under low wind conditions, which could intensify the formation of the diurnal thermocline in the 'skin and sub-skin layer' (Barton 1998, 2001; Donlon et al. 2002). The comparison presented in this work was made with *in situ* data mostly obtained on calm days, which are not the conditions normally associated with this area, since the annual mean wind speed is 6.19 m s^{-1} (SMN 1992). Furthermore, one of the main characteristics of the study area is that the constant winds produce a homogeneous water column all year round (Piccolo 1998).

Another factor that could lead to differences between *in situ* and satellite data is the different ways of measuring *in situ* SST. In our *in situ* dataset, SST was taken at depths between 0.2 and 5 m, and it is possible that this did not coincide strictly with the 'skin' layer temperature (Hosoda et al. 2007). Moreover, the NLSST algorithm used to generate MODIS SST maps was developed using *in situ* measurements collected in the Northern Hemisphere, and the atmospheric conditions may not be representative of our study area leading to less accurate results (Brown and Minnet 1999; Williams et al. 2013).

The statistical results obtained in this study are comparable to other coastal studies where MODIS SST was validated with *in situ* measurements. In the western Pacific coasts, Barton and Pierce (2006) obtained a bias (°C) of –0.32. Hosoda et al. (2007) found a bias of –0.06°C and RMSE of 0.81°C in the western North Pacific. Lee et al. (2010) validated SST on the Taiwan coast with a bias (°C) of 0.42 and RMSE (°C) of 0.86. Recently, Williams et al. (2013) presented the validation of MODIS-Aqua SST with *in situ* data from the San Matías Gulf (Argentina). Their results showed R^2 of 0.89 and also addressed an overestimation of the satellite product. Even though the value of the bias is higher in our study, the values of RMSE are similar and R^2 are higher.

The statistical analysis of SST variability with Census X-11 demonstrated that there was no positive (warming) or negative (cooling) tendency in the study area between 2002 and 2010. Inter-annual variability ($T(t)$) is not significant for this period either. On the other hand, the seasonal signal is very strong, with the highest amplitude in coastal waters (15°C) decreasing towards the open ocean. Spatial distribution of SST in the study area is clearly influenced by changes in the shallow, bathymetric, homogeneous waters of the Bahia Blanca estuary and semi-enclosed Anegada Bay, the Gulf Current in the inner shelf, and stratified waters of the mid-shelf. It is worth noting the major influence of the tidal flats of Bahia Blanca estuary and Anegada Bay in the heat exchange between the atmosphere and the sea. Both zones have a rapid response to air temperature changes, reaching maximum SST in January (26°C) and minimum in July (7°C). The inner shelf has lower seasonal signal amplitude, since it effectively mixes waters with deeper bathymetry, slowing the response of SST to air temperature variation. In addition, the incoming relatively warmer Gulf current does not allow a sharp decrease in temperature, presenting a relatively high SST minimum (11°C). A thermal front is usually formed between both subsystems (Rivas and Pisoni 2010). Finally, mid-shelf stratified waters have the lowest seasonal temperature amplitude. It is worth highlighting that SST spatial and seasonal distribution in this study agreed with previous results based on *in situ* measurement in the study area (e.g. Martos and Piccolo 1988; Piccolo 1998; Perillo and Piccolo 1999; Cuadrado, Piccolo, and Perillo 2002; Lucas et al. 2005).

The results of the validation of SST in the coastal and inner mid-shelves of southwest Buenos Aires Province proved the accuracy of the satellite product. It is now possible to use MODIS SST maps for monitoring the variability of SST for the last decade and linking this to biomass variability in our area of interest. Furthermore, the spatial and temporal analysis of the product in the study area demonstrated that it is a useful and highly recommended product to use in environmental studies, being well capable of replacing bulk measurements, which are very hard to obtain.

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