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ENVIRONMENTAL CHARACTERISTICS OF SAN MATÍAS GULF OBTAINED FROM LANDSAT-TM AND ETM+ DATA

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ABSTRACT

The San Matías Gulf, located between 40 47' S and 42 13' S on the Atlantic coast of South America, with an area of approximately 18 000 km^2, is the second largest in Argentina. This gulf has been studied by means of historical data obtained in oceanographic campaigns carried out before 1990 and with satellite images of low-resolution (1000 m) NOAA-AVHRR obtained from 1985. The analysis of this information permitted to infer some environmental characteristics related to temperature, salinity, productivity and circulation. The objective of the present work is to analyze LANDSAT-TM and ETM+ data from 1997-2003. Approximately 30 free of clouds images, obtained in different times of the year, were processed. The thermal channel allowed to obtain a detailed distribution of surface temperature, to identify thermal fronts and to analyze its variability along the year. Also, this channel and channel 1 permit to observe the influence, in the southern part of the gulf, of the water coming from the continental shelf and San José Gulf. The results obtained did not only contributed to corroborate the environmental characteristics already inferred previously from cruise data, but also, to identify others, so far unknown.

INTRODUCTION

The San Matías Gulf (Figure 1) has been studied with data collected in oceanographic cruises previous to 1990 and, to a lesser extent, with low resolution satellite data AVHRR (Advanced very High Resolution Radiometer) on board the NOAA (National Oceanic and Atmospheric Administration) satellites. Being a semi-enclosed basin, the distribution of the physical properties and its evolution are governed basically by the interchange with the atmosphere and with the open ocean through the mouth of the gulf. Brandhorst and Castello (1971) find a relative maximum in the surface salinity in the northern sector of the gulf whose influence is projected towards the north, like a narrow tongue over the shelf, until 38° S. On the other hand it is known that the influx of the shelf water from the south-east sector regulates the physical conditions found in its southern sector and even in the San José Gulf. However, although the exchange with the open sea affects the physical conditions found inside the gulf, due to its particular geometry (shallow and with a mouth limited by a pronounced sill), the atmospheric forcing is of the greatest importance (Rivas, 1990).

As a consequence, the surface signal acquires singular relevance and its observation is highly useful in the study of the San Matías Gulf. Remote sensor on board of satellite has the ability of monitoring this type of signals and the information obtained on this way has the advantage of covering a large area, virtually simultaneously and repetitively. The satellite systems LANDSAT-TM (Thematic Mapper) and LANDSAT-ETM+ (Enhanced Thematic Mapper Plus) though designed for terrestrial applications, possess characteristics that make them potentially useful for coastal oceanic studies. This is due, on the one hand, their capacity to estimate the sea surface temperature and the suspended matter distribution in the upper layer of the sea. On the other hand, their high spatial resolution allows to observe small scale processes particularly important in coastal regions and to study the boundary of the coastline without the risk of signal contamination by adjacent land as is the case of low resolution systems, in particular the NOAA-AVHRR. Taken into account the mentioned advantages, the aim of the current paper is to analyze diverse aspects of the San Matías Gulf by processing a series of images obtained during 1997-2002 in order to corroborate and explore environmental characteristics already inferred from cruise data and to identify others, so far unknown.

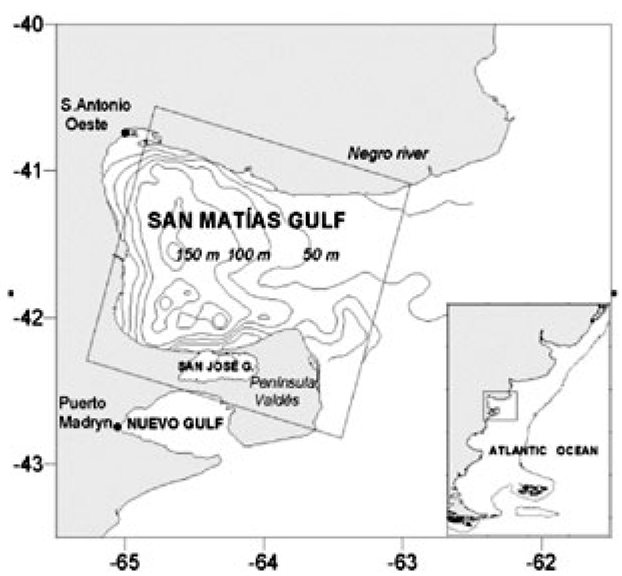

Figure 1. San Matías and San José gulfs (the rectangle indicate the area covered by the LANDSAT images)

RESEARCH AREA AND BACKGROUND

The San Matías Gulf (Figure 1) is situated between 40° 47´ S and 42° 13´ S on the Atlantic coast of South America and it is the second largest in Argentina with an area of approximately 18.000 km. Its maximum depth is over 200 m and approximately 45% of the gulf is less than 100 m deep (Piola and Scasso 1988). Its mouth, which communicates with the exterior shelf, is approximately 100 km long and presents a 70 m sill. Towards the east the continental shelf is about 80 m deep. A particular characteristic of the gulf are two large, 160m deep depressions situated symmetrically respect the parallel 41° 40´ S. From the PESQUERIA cruises (Lusquiños, 1971) areas of higher temperature and salinity have been identified in the northern sector of the Gulf, whose origin was attributed, at least partly, to their lower renewal rate. Carreto et al. (1974) conclude that in spring the gulf presents two zones with markedly different water masses. One, named by the authors as "typical water of the Gulf", is found in the north and east sector and is characterized by high temperature and salinity, a marked thermocline and limiting concentrations of nitrates (phytoplankton population dominated by dinoflagellates). The other, named "waters of exterior origin" and found in the south and south-east sector, is of lower temperature and salinity, lacks stratification and possesses relatively higher concentrations of nitrates (the phytoplankton population in this case is dominated by diatoms). Krepper and Bianchi (1982), based on the analysis of seasonal variation of the heat contents of the water column, find that the gulf's waters, being more isolated and thus more directly affected by the surface flux of heat, have higher temperature and thermal amplitude than the rest of the waters of the southern sector of the continental shelf. Piola and Scasso (1988) point out the presence during a great part of the year of a zonal front situated near 41° 50´ S, which separates warmer and saltier waters of the north sector from the colder and less salty ones that ingress from the south. From the analysed data the authors determine that the difference of temperature between both regions reaches 3° C, becoming negligible in the winter. Moreover, from the property distribution, they find that in summer the circulation in the north part is dominated by a cyclonic gyre of 70 km in diameter centered in 41° 15´ S, and that towards the south, although the circulation cannot be well defined with the available data, the presence of another cyclonic cell of smaller dimensions is apparent. Scasso and Piola (1988) interpret that the maximum salinity is due to the fact that the gulf's waters are subjected to a greater evaporation than those of the adjacent shelf. Rivas and Beier (1990) coincide in pointing out the influx of colder and less salty water through the south part of the gulf's mouth but they estimate that the maximum salinity originates from the isolation of the interior waters.

The tide is of semi-diurnal regime and reaches amplitude of 6 m in some coastal areas. The associated currents, despite the few available observations, are of 1 m/s according to Mazio and Vara (1983), while later observations estimate around 0.4 m/s (Framiñan et al., 1991). The numerical model implemented by Beier et al. (1989) coincides in pointing out the presence of a cyclonic gyre in the northern sector and the influx of shelf water through the southern sector of the mouth.

In the entire Patagonian Shelf the mixing induced by the tidal currents brings about high levels of dissipation and, in zones of particular topographic shoals can inhibit the formation of a seasonal thermocline, creating in spring and summer thermal fronts that define the border between stratified and vertically mixed waters. In the zone two tidal fronts have been identified, one to the south-east of Valdés Peninsula and one in the northern sector of the mouth of the San Matías Gulf (Glorioso, 1987; Glorioso and Flather, 1995; Rivas and Dell' Arciprete, 2000; Bava et al., 2002).

DATA AND METHODOLOGY

The current work is based on the interpretation and analysis of LANDSAT TM and ETM+ satellite images, launched in a heliosynchronic orbit with 8 days' shift. Both sensor possess a swath width of approximately 185 km and 7 spectral bands in the optical, near, middle, far and thermal infrared bands; all of them with 30 m spatial resolution, except the thermal channel with 120 m for TM and 60 m for ETM+. The last one has also a panchromatic channel with 15 m resolution. The wavelengths have been selected for terrestrial applications as their main purpose, nevertheless the inclusion of channel 1 in the blue-green and one in the thermal band makes both sensors very useful to study the ocean and coastal waters. Any way, it is necessary to take into account that due to the fact that these sensors only possess one infrared thermal channel, it is highly complicated to make an atmospheric correction to obtain real sea surface temperature (SST) values. It is, however, simple to obtain the brightness temperature, i.e. that of a black body emitting the same quantity of electromagnetic radiation as that detected by the sensor. Thus, from now on, SST represents the brightness surface temperature and will be calculated according to Planck's equation, with water emissivity equal to 1. Although SST values are not corrected by the atmosphere, they can provide a clear idea of the spatial and temporal variations, especially if we assume the same atmospheric effect in the entire area under study. Part of the thermal infrared radiation emitted by the sea surface is absorbed by the atmospheric water vapour thus the brightness temperature will always be lower than the real one and the difference between them will be based on the amount of water vapour present in the atmosphere.

A set of 30 images obtained between 1997 and 2003, supplied by Argentine Comisión Nacional de Actividades Espaciales (CONAE), were analysed. The images correspond to the Path 227 and Row 89, covering practically the entire San Matías Gulf with only the north-west end excluded (Figure 1). As a first step in the processing, a level 5 ETM+ image was selected and georeferenced in the Gauss Kruger projection (Transverse Mercator), FAJA 4, spheroid WGS84 using ground control point previously measured with GPS. Next, the remaining images were co-registered in respect to the previous one in order to compare the information provided by each of them. Then the land was masked using channel 7 in order to isolate the water and highlight the observed patterns. Finally, Channels 1 and 6 were separated from the set of masked images and maps of SST were generated applying Planck's equation to radiance values obtained from the last one.

ANALYSIS OF INFORMATION AND RESULTS

The SST maps were represented in grey scale, in continuous values and grouped by month in order to do a preliminary analysis. Later, they were separated in two groups according to common characteristics. The first set corresponded to images from October to March and the second, from April to September.

The SST maps corresponding to the first set (17 altogether), some of which are shown in Figure 2, reveal a SST distribution characterized by the presence of a thermal front that extends from the northern sector of the mouth towards the south, reaching the midpoint of the gulf's entrance, and then, turning towards the west to descend again towards the south. The position of this front on the different days is evident, its temporal variability is clearly noted and it can be observed that in any case reaches the west coast, drifting away at different distances on different dates. In this manner the gulf is separated in two sectors with water masses of different SST, being the southern colder and smaller in all the dates analyzed. As it was stated while Piola and Scasso (1988) only mentioned one zonal front situated near 41° 40´ S, Carreto et al. (1974) included the western sector of the gulf in the warmer and saltier waters. No previous work, based on data obtained from traditional oceanographic cruises, could identify the northern sector of the front parallel to the mouth. Figure 2 shows that this part of the thermal front is determined by a strip of water too narrow to be identified clearly with traditional field data unless the sampling would be specifically designed for this purpose. It can be observed that there exists a certain correspondence between the positions of the front suggested by Figure 2 and the shallower zone situated between the two deepest depressions (Figure 1). If the physical properties distribution is indeed related to bathymetry, this would prove the hypothesis set forth by Piola and Scasso (1988) that claimed that there is a certain degree of coupling between the water circulation and the bottom topography .

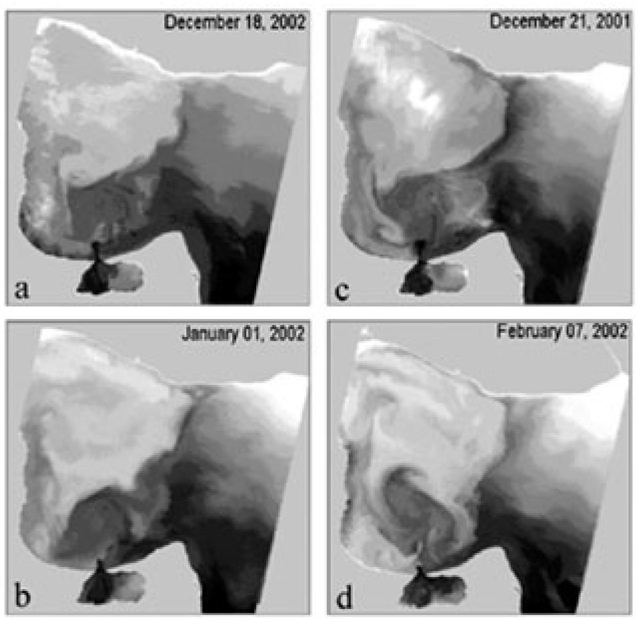

Figure 2. SST distribution for four different dates from October to March

Moreover, a mass of colder water outside the gulf can be clearly noted. This water mass comes from the south and goes round the Valdés Peninsula until the mouth of the San José Gulf interacting with local waters and those of the southern sector of the San Matías Gulf. It can be seen in some cases entering San José Gulf, thus causing the water temperature of this gulf to fall, while outgoing, waters from San José Gulf can be observed mix with those of the southern sector of the San Matías Gulf. These processes can be observed in Figures 3a and 3b, representing the San José Gulf and the southern region of San Matías Gulf . Channel 1 is the one that penetrates deeper into the water and the most sensitive to the suspended matter, being a good indicator of the circulation. Figure 3c and 3d shows channel 1 corresponding to the thermal image in 3a and 3b, showning in detail the turbidity of the interacting waters as well as their displacement. It can be noted that both the incoming and outgoing waters of the San José Gulf are not only colder but also more turbid than those surrounding it, and eddies created in the mouth of the gulf can be clearly seen.

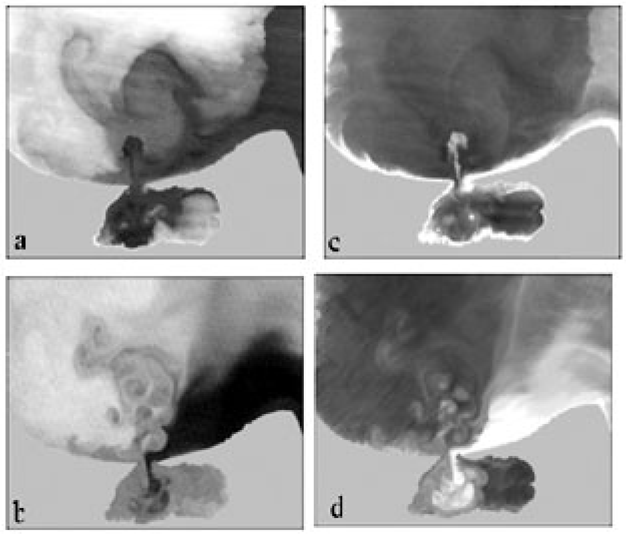

Figure 3. Channel 6 and channel 1 cobering San José gulf the southern region of San Matías gulf

The second set resulted in a lower number of images (13 altogether) due to increased cloudiness in the period of the recording. It starts in April, when the previously indicated thermal front begins to disappear and the SST spatial distribution of the gulf's water is more uniform. As an example, Figure 4 shows the SST maps corresponding to June 1st, 2001 and June May 30th, 2002. In all cases, the total absence of the thermal front shown in Figure 2 can be noted as well as the presence of a cold water mass originating from the south. This situation remains stable until September when the north-south front starts forming again and is well formed by October-November.

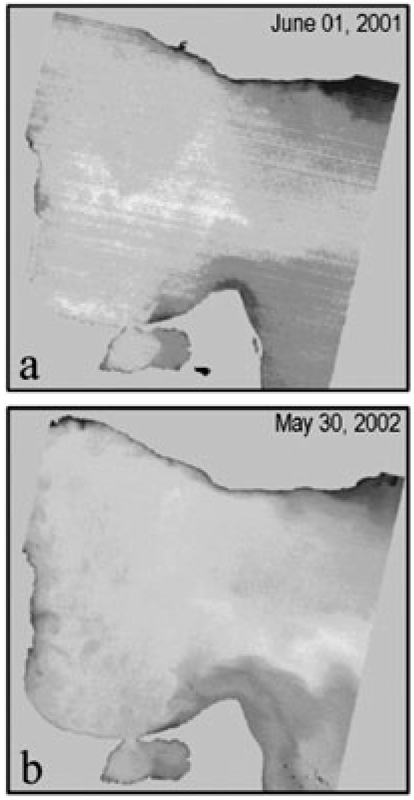

Figure 4. SST distribution for two different dates from April to September

As a first step to calculate the SST it is necessary to convert de count values obtained by the sensor into values of energy emitted by the surface. For this it is necessary to use the sensor's calibration constants obtained before the satellite was launched. Taking into account that the Lansat TM system was lunched in 1984 and there have been a deterioration of its sensors, only the information obtained by the ETM+ has been used for a quantitative analysis. The AVHRR sensor, on board of the NOAA satellites, has two channels in thermal infrared and one in the middle infrared; therefore in this case it is possible to estimate the effects of the atmosphere and to obtain SST values very close to the real ones. Nevertheless, it is alse possible to make comparisons between the SST values obtained by both sensors. Figure 5 shows AVHRR monthly SST values averaged for the period 1987-1998 (Pathfinder data, monthly mean values, spatial resolution of 9 km or 0.08°) in two points of the San Matías Gulf, one representative of the northern part (41° 11´ S 64° 28´ W) and one of the southern part (42° 4´ S 64° 17´ W) as well as the SST values obtained from ETM+ for those two points. As expected, the SST values obtained from AVHRR data are always higher than those calculated from ETM+ given that the latter was not atmospherically corrected. Despite these systematic differences, it can be noted that both sets of data show slight difference between the southern and the northern sectors for May, June and July whereas it increases in September and reaches its maximum (about 2 degrees) in December, January and February. From the scarce field information available Piola and Scasso (1988) claim the existence of a zonal front which separates the northern warmer waters from the relatively colder ones of the southern sector and they show that the temperature difference range between 1 and 3°C in February and September and is virtually imperceptible in June. Although the information contributed by both sensors allows to verify and explore the results obtained from in situ data, the low relative resolution of the AVHRR sensor does not permit to observe the details detected by TM or ETM+ sensors which are important for the environmental description of the region. For example, Figs. 3 c and 3d show the vortices originated by the tidal flow in the mouth of the San José Gulf. They are fundamental in the regulation of the exchange property because there is an asymmetry between the flow entering and leaving the gulf in each tidal cycle and, in consequence, a fraction of fluid is not returned through the mouth (Wells et al., 2003).

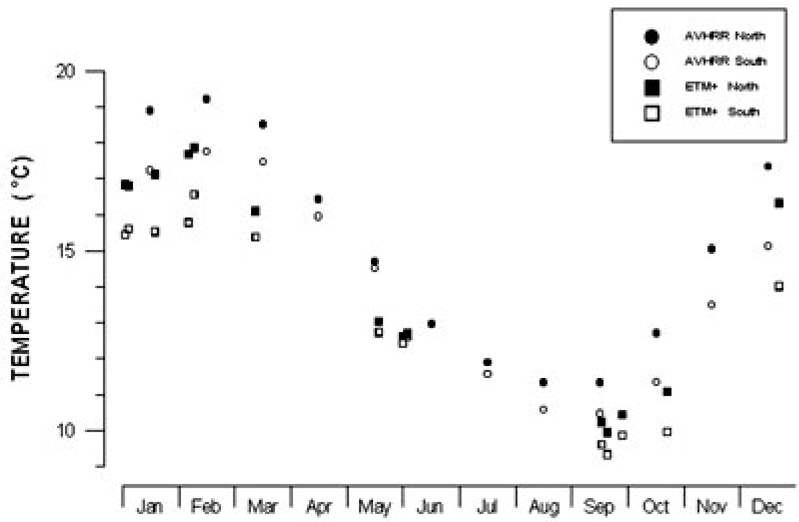

Figure 5. AVHRR monthly SST values averaged for the period 1987-1998 and ETM+SST values

DISCUSSION AND CONCLUSIONS

The SST of the San Matías gulf is determined basically by the surface flow of heat and the depth of the mixed layer. The surface heat flux changes during the year: the sea gains heat between September and March, and loses energy between April and August. On the average throughout the year the sea has a net gain of heat which must be compensated by horizontal advection of cold water in order to prevent an increase in the average temperature. Climatological values obtained from the NCEP re-analysis (Kalmay et al., 1996) illustrate the mentioned characteristics of the surface heat flux representative of the zone.

In winter the loss of energy through the surface favours the vertical convection and the water column is totally homogeneous (Rivas, 1990; Piola and Scasso, 1988). Assuming that the loss of energy is the same in the entire study area , the cooling must be greater in the less deep zones; accordingly the surface temperature (which in that period of the year coincides with the temperature of the whole water column) must be lower in the shallower regions; nevertheless as the vertical convection increases the horizontal mix, the SST differences are small.

Since spring the heat-gain at the air-sea interface favors the development of a seasonal thermocline whose depth is determined by the balance between the surface flux and the combined mixing action of wind and tide. In some shallow regions or regions with marked topographic steps the strong tidal currents that characterize the region produce enough seabed turbulence to inhibit the development of the seasonal thermocline and to keep the water column homogeneous even in summer, creating the tidal fronts identified in the region. These fronts separate the stratified zones with a warm surface layer and a cold bottom layer from those with homogeneous temperature from the surface downwards. On the surface, the mixed zones have a lower temperature than the stratified ones since heat received through the surface is distributed in the whole water column. Near the studied area two tidal fronts have been identified, one situated in the northern sector of the mouth of San Matías Gulf and the other east of the Valdes Peninsula (Rivas and Dell' Arciprete, 2000; Bava et al., 2002). Figure 6 combine images corresponding to the initial phase of the surface warming, showing that SST it is not uniform and is higher in the stratified zones, with a north-south front almost parallel to the mouth of the gulf and stronger in the south. Later the advection of cold water originating in the Peninsula front which enters the gulf through the southern sector of the mouth and the complex flows generated in the mouth of the San José Gulf cool practically the whole surface of the southern sector of the San Matías Gulf and cause the thermal front to turn towards the west. The thermal front observed in the images has been already inferred from fieldwork data by Carreto et al., 1974; Piola and Scasso, 1988 and Rivas and Beier, 1990. In addition, the influx of cold water to the gulf explains the fact that the average temperature of the gulf does not increase yearly despite the net heat annual gains on the surface.

As shown in Figure 5, temperatures estimated from ETM+ sensor in the northern (warmer) zone and in the southern (colder) zone present a well defined seasonal cycle with values lower than those estimated with the NOAA-AVHRR systems since the latter take into account the absorption produced by the atmospheric water vapour. The differences between both sets of data increase in the summer reaching 3°C and decrease in winter. This indicates that the amount of vapour in the atmosphere is greater in summer than in winter, which is coherent since the saturation pressure of the water vapour in the atmosphere increases with air temperature. Paradoxically, the source of atmospheric vapor is greater in winter. In fact, the fresh water flow from the sea to the atmosphere is greater in winter than in summer (Rivas and Ripa, 1986) as rainfall in the zone is seasonally uniform and in winter the difference of the airsea temperatures produces instability in the lower layer of the atmosphere (as the sea is warmer than the air) and the vertical convection produced favours the evaporation as it inhibits the saturation with water vapour of the air in contacts with the sea.

The present work has been based on sea surface temperature derived from satellite information which show marked differences from those obtained in oceanographic cruises. The latter have the advantage of "in situ" observations, usually at different depths, nevertheless they were obtained from specific points, sometimes separated by great distances and also at different times, thus missing details between observations. For the same reason the results are generally difficult to extrapolate around the sites under observation and at a specific moment. The satellite data have the disadvantage of referring only to the surface and, at the same time, of being less accurate since they were collected from approximately 800 km height with the atmosphere between the sensor and the sea surface. However, this type of data has numerous advantages, among others: a) they cover an area (determined by the width of the swath), b) each value obtained is the average of a sub-area (depending on the sensor's resolution), c) all the data is obtained within seconds or minutes, i.e. virtually simultaneously, d) the observation process is repetitive (defined by the revisit of the satellite), and e) at present time it is possible to obtain a temporal series of several years' length.

The results achieved in this work make it possible to confirm that high resolution satellite information provided by the LANDSAT-TM/ETM+ systems has allowed not only to confirm the conclusions previously reached by other researchers through data collected in oceanographic cruises, but also to add more detailed information in different aspects related to the dynamics of the San Matías Gulf. In particular, the thermal front is observed along its entire extension showing its position in detail on each day, thus determining its spatial-temporal variability. The understanding of this variability is highly important to infer the dynamics of the gulf as well as its environmental characteristics, at the same time it allows to determine the area of oscillation of the front and to correlate its position with bathymetry. In the same way, the images clearly show the interaction of waters coming from the south and those of the San José Gulf with the San Matías Gulf . In the latter case processes not registered before are observed, such as minor eddies or jets, generated probably by the interaction of egressing waters with the borders and the bottom of the mouth of the San José Gulf . Moreover, it is important to mention, that even though there are previous studies using satellite data (Rivas and Dell'Arciprete, 2000; Bava et al., 2002), these were carried out with NOAA-AVHRR data whose spatial resolution does not permit to detect details observed with the 120 m and 60 m resolution of the TM and ETM+ sensors respectively.

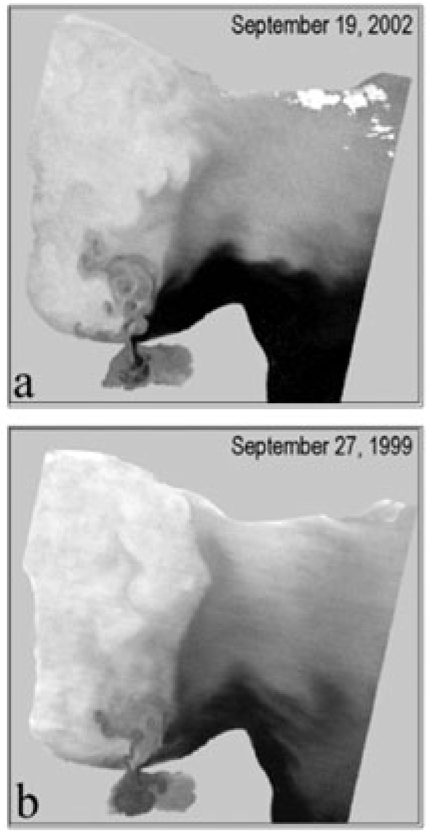

Figure 6. SST for the initial phase of the surface warming, for two different date

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