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ANALYSIS OF SUPERFICIAL ANOMALIES OBSERVED IN IBERIA SOUTHWEST COAST - NUMERICAL MODEL APPROACH

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Summary: In this paper a characterization of observed sea surface anomalies in the Spanish southwest coast (more specifically Nerja- La Herradura and Cabo de Gata areas) is done. This study aims to explain the origin of observed anomalies and their possible relation with submarine groundwater discharges (SGD). The data analysis was complemented with model results forced with realistic forcing and initial conditions.

1 INTRODUCTION

Within the framework of a project, to determine the fresh water discharges flow intensity and location associated with submarine groundwater discharges (SGD), an extensive set of measured data was collected (*in situ* and remote). On June 13 2009, sea surface temperature (SST) with a spatial resolution of O (10 m) was measured with a sensor installed in an airplane. This was followed by two field campaigns in November/December of 2009 and another in November/December of 2010. The first campaign was focused on the water column anomalies (more than 300 CTD profiles were measured) and collection of flow properties to validate the numerical model (e.g. sea surface height and currents). The second campaign was focused on surface anomalies. In this campaign, in addition to the CTD profiles, superficial (~20 cm depth) salinity and temperature measurements were performed along the boat trajectory with a high spatial resolution.

Only the superficial data (remote SST data and salinity along ship track) reveal significant anomalies. However, the SST data exposed anomalies with a spatial scale much greater than the salinity surface anomalies. In order to help to explain the observed temperature and salinity surface anomalies and try to establish their most probable causes, a numerical model was implemented using realistic initial and forcing conditions (tide, wind, atmospheric pressure and regional density gradients).

For Cabo de Gata the airplane SST data (June 13, 2009) revealed several negative anomalies. The larger one was associated with the Atlantic Jet. There were also more local anomalies linked with internal waves activity (more specifically internal tides). Internal tides can be dissipated on continental slopes and shelves[1] or even reach beach surf zone[2]. Internal tides can bring pulses of cold water shoreward and produce large vertical temperature differences[2]. In Cabo de Gata area no significant salinity anomalies were measured in the 2010 *in situ* field campaign. For Cabo de Gata area it was concluded that no SGD or superficial discharges exist -- those that may exist have a sporadic nature (e.g. Cerro de los Guardias).

In the case of Nerja-La Herradura SST negative anomalies were also observed. The major ones can also be linked with internal tides activity. The exception was a very local anomaly in Playa de Maro very likely associated with a fresh water discharge. A few superficial salinity plumes were identified in this area in the December 2010 field campaign. However all of them were linked with superficial fresh water discharges. All anomalies detected were quite localized (a few hundred meters).

In this paper after the “Introduction” chapter we have presented the “Study area” and “Methodology” adopted to analyze the surface anomalies. This chapter is followed by the “Results” chapter where the surface water field data and the model results are presented and discussed. Finally the “Conclusions” are summarized.

2 STUDY AREA

Two areas were considered in this study: Nerja – La Herradura and Cabo de Gata. These were chosen because of the hydrogeology characteristics of the adjacent land areas. These areas also reveal a good potential to have SGD.

2.1 Nerja - La Herradura

Nerja - La Herradura area is located between the Strait of Gibraltar and Cabo de Gata. This coastal area is under the influence of the Atlantic Jet that enters the Mediterranean Sea through the Strait of Gibraltar. The jet transports water from the Atlantic Ocean less dense than the Mediterranean water. The oceanographic characteristics of the area are influenced by the Atlantic Jet in the northern part of the Alboran Sea. The jet flows around the large anticyclonic gyre that usually occupies the western Alboran basin (Figure 1).

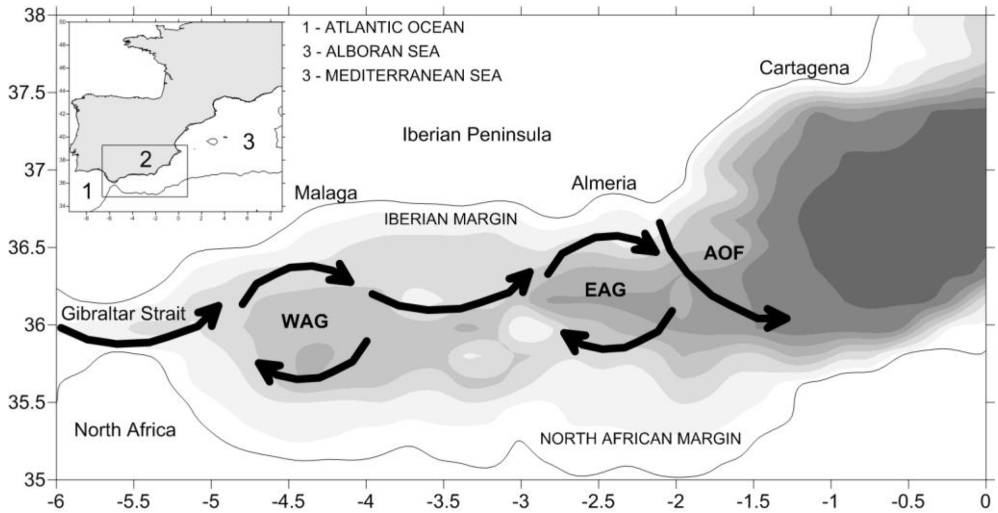

Figure 1 – General superficial circulation in the Alboran Sea.

The northern edge of the Atlantic Jet is the southern boundary of the upwelling area that extends from Estepona (between the Strait of Gibraltar and Malaga) to Almeria. The strong gradient of properties between the water north of the Atlantic Jet and inside the Jet, produces one of the most intense fronts of the Mediterranean Sea.

The upwelling processes in the region are enhanced by two different mechanisms: i) the departure of the Atlantic jet from the Spanish coast, and ii) the wind driven offshore transport induced by “Ponientes.” Both mechanisms are shown to be present approximately 50% of the year[3]. The frequency of “Ponientes” (westerlies) observed in Tarifa, is approximately 50%[3]. Tide propagation through the strait of Gibraltar gives rise to internal solitons packets propagating eastward. The density differences, provides the necessary stratification. Strong tidal flow over the Camarinal Sill (strait of Gibraltar) regularly produces solitons of amplitudes of 50 to 100 m[4].

2.1 Cabo de Gata

Cabo de Gata is a cape located in a transition zone. This area is a confluence point of the Atlantic Jet and Catalan Current. The latter current originates in the northern area of west Mediterranean basin precisely in the north point of Corsica. In this point the sows of MAW west and east of Corsica join and form the so-called Liguro-Provenco-Catalan Current, which is the ‘Northern Current’ of the Basin along the southwest European coasts[5]. Mesoscale activity is more intense in winter than that in summer because it becomes thicker and narrower. There is also strong seasonal variability in the mesoscale in the Balearic Sea. Intense barotropic mesoscale eddy activity propagates seaward from the coastline around the sea from winter to spring, and induces a seasonal variability in the open sea.

3 METHODOLOGY

Superficial anomalies observed in Nerja-La Herradura and Cabo de Gata were analyzed based on realistic numerical model simulations. The MOHID numerical system was the tool implemented. Two types of superficial anomalies were examined:

- High resolution (O(10 m)) SST observations for June 13, 2009;
- *In situ* data obtained during field campaigns of December, 2010

The main goal of this analysis was to check if the observed anomalies could be linked to submarine groundwater discharges (SGD), if not, suggest the origin of the anomalies. The data obtained in both periods was compared with model simulations for the same period assuming realistic high frequency forcing (tide, atmospheric pressure, wind and regional density gradients) and bathymetric data. The idea was to use the model to test the hypothesis and help in the identification of the physical processes behind the anomalies. The potential link between the negative temperature and salinity surface anomalies SGD's was based on a simple conceptual model. A SGD generates a buoyant (lower density) plume, with the tendency to rise at the surface layers due to the intense density differences between fresh and Mediterranean Sea water. The plume can reach the surface if the thermal stratification is not too intense. The plume due to the intense mixing will have a temperature similar to the one of the bottom layers and salinity slightly smaller than the surrounding environment.

3.1 MOHID numerical system

The MOHID system hydrodynamic model uses a finite volume approach[6] to discretize the equations in a structured grid. In this approach, the discrete form of the governing equations is applied macroscopically to a cell control volume. This makes the actual way of solving the equations independent of cell geometry and allows the use of a generic vertical coordinate[6]. The equations are discretized horizontally on an Arakawa-C staggered grid. Temporal discretization is performed by a semi-implicit (ADI) algorithm with two time levels per iteration. For ocean processes, special care must be taken in the discretization of the baroclinic force, advection/turbulent diffusion of momentum, heat and mass. For the baroclinic force, the MOHID system uses a z-level approach for any type of vertical coordinate. Basically, this methodology integrates the horizontal density gradient into the Cartesian space. The horizontal and vertical advection of momentum, heat and mass is computed using a TVD-Superbee method. The turbulent transport processes are simulated assuming Fickian approximation. The vertical turbulent viscosity/diffusivity coefficients are computed using a k-epsilon model, while for the horizontal, constant coefficients are assumed. The MOHID system is coupled to the General Ocean Turbulence Model (GOTM)[7]. GOTM is a water column model which simply allows a choice between some standard turbulence parameterizations. The ADI approach avoids computing the internal and external modes with different time steps (mode splitting approach). An efficient way to dissipate high-frequency noise is the use of a biharmonic filter for the velocities. The advantage of this methodology relatively to the more traditional approach of increasing the Fickian diffusion artificially is its ability to dissipate the high-frequency processes without significantly changing the lower-frequency processes.

3.2 Model implementation

In this study a numerical model was implemented using until 5 nesting. The first domain (Level 1) was a 2D barotropic tidal and atmospheric pressure driven model, which uses the FES2004 global solution[8] to impose the astronomic tide in the open boundary. The subsequent nesting levels are 3D baroclinic models (Level 2 to Level n – n is the number of nesting levels implemented)[9].

The Open Boundary Conditions (OBC) of Level 2 are defined adding to the solution of Level 1 (high frequency) the low frequency Mercator Ocean (MO) model solution[10], which has a resolution of 0.0833º for this area. Inverted barometer effect (water level variation due to pressure gradients) was imposed at Level 1 Atlantic open boundary. The surface boundary condition for momentum and heat is imposed using the Global Forecast System (GFS) weather prediction solution (50 km of horizontal resolution). Level 1 covers the entire Mediterranean and Level 2 covers the Gulf of Cadiz and the western Mediterranean (Figure 2). Level 1 and Level 2 had both the same horizontal resolution similar to the MO solution 0.06º.

To characterize the hydrodynamic properties in the coast of Nerja-La Herradura and Cabo de Gata (e.g., local scale processes), three more domains were nested in Level 2. The third domain covers Nerja-La Herradura (Level 3a) and Cabo de Gata (Level 3b) coast and both had 0.01º (~1 km) of resolution (Figure 2).

The fourth domain in the area of Nerja-La Herradura (extends from Punta de Torrox and La Herradura Coast with 0.002º (~200 m) of resolution. A fifth domain was only added to the Cabo de Gata area with 0.0004º with the goal of simulating with high detail the SST negative anomaly located near Morrón de los Genoveses.

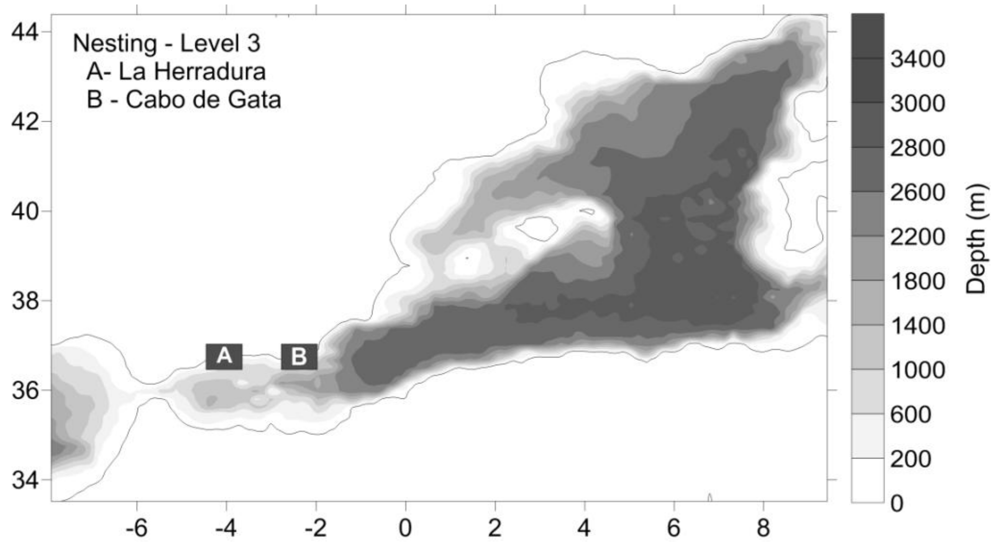

Figure 2 – Level 2 overlap by Level 3 domains. Blue squares Level 3 domains : a) Nerja – La Herradura and b) Cabo de Gata.

Level3b covers the entire Cabo de Gata coast with a 0.01º horizontal resolution extended from Almeria (west boundary) to Carboneras (east boundary). Level 4b covers the entire east coast of Cabo de Gata from Cabo de Gata promontory to Carboneras with a spatial step of 0.002º. The vertical resolution differs from model to model according to model domain depth. However, in all 3D models a z level discretization is assumed below the 10 m depth and above a sigma one. The sigma layers are of O (10 cm). For surface forcing GFS model solutions were imposed in all domains.

3.2 Simulation of June 13th of 2009

A key data set for the entire work developed in the framework of this project was the high resolution (O(10 m)) SST airplane remote images. These images were collected for June 13, 2009 at approximately midnight and revealed temperature anomalies. Some of these negative anomalies were initially linked with SGD's.

The simulations were made for the period of 7 to 14 June, the first 4 days being considered as spin-up. A qualitative validation was done. The 3D structure of the simulated temperature and vertical velocity was correlated qualitatively with the observed SST.

4 RESULTS AND DISCUSSION

In a first analysis of the SST images measured from the airplane we explored the hypothesis that observed negative anomalies could be generated by submarine groundwater discharges. However, subsequent *in situ* measurements reveal no salinity anomalies associated with theses anomalies. Only in Nerja-La Herradura were significantly negative superficial salinity anomalies observed in the December 2010 field campaign. However, all salinity anomalies had spatial scales much smaller than the ones observed in the remote SST data. A clear link was established between salinity anomalies and known superficial fresh water discharges. The numerical model was used to confirm the location and flow intensity of the main superficial fresh water discharges proposed by the hydro geologist expertise. In this chapter the focus was the SST negative anomalies. An explanation of their origin is suggested.

4.1 Cabo de Gata

The SST airplane images for Cabo de Gata presented clear anomalies for June 13, 2009 (red squares - Figure 3). However, the December 2010 campaign did not reveal any significant superficial salinity anomalies. This result lead to the conclusion that the SST anomalies captured by the airplane were not related to SGD's. The first anomaly was located along the entire west coast of Cabo de Gata (first red square counting from left to right). This large anomaly was clearly generated by the influence of the Atlantic Jet. The signal of the Atlantic Jet reaching the west coast adjacent to Cabo de Gata was very clear in the regional SST satellite image (Figure 4). This image for the Cabo de Gata west coast presented SST values of 19-20ºC. These values coincide with the lower limit of SST airplane image (Figure 3). SST data shows that the coast westward to Cabo the Gata was an area of lower temperatures (influence of the Atlantic Jet). The temperature was higher in the coast eastward to Cabo de Gata (influence of the Catalan current). The model results for 2, 3b and 4b nesting levels presented similar SST gradients when compared with the airplane image (Figure 3).

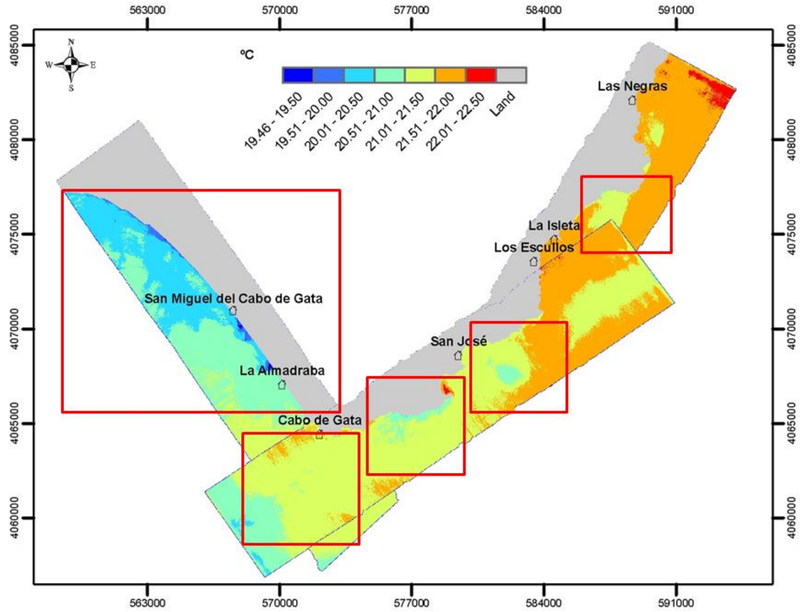

Figure 3 – SST anomalies in Cabo de Gata area on June 13, 2009. Main localities and beaches in the area of interest (source: http://www.degata.com).

The SST airplane image presented sharp horizontal gradients of temperature south of Cabo de Gata. These gradients or anomalies cannot be related with a SGD. This assumption is based mainly on the fact that this area has a depth of some 100 m. At these depths a SGD with 100 l/s (maximum flow limited established in a preliminary phase by the hydrogeology experts for the upper limit of a SGD) could not generate the strong SST negative anomaly present in the airplane image. The initial dilution of the order of 100-1000 (typical dilution of a discharge at 50 m) would dissipate any signature of the SGD plume at the surface.

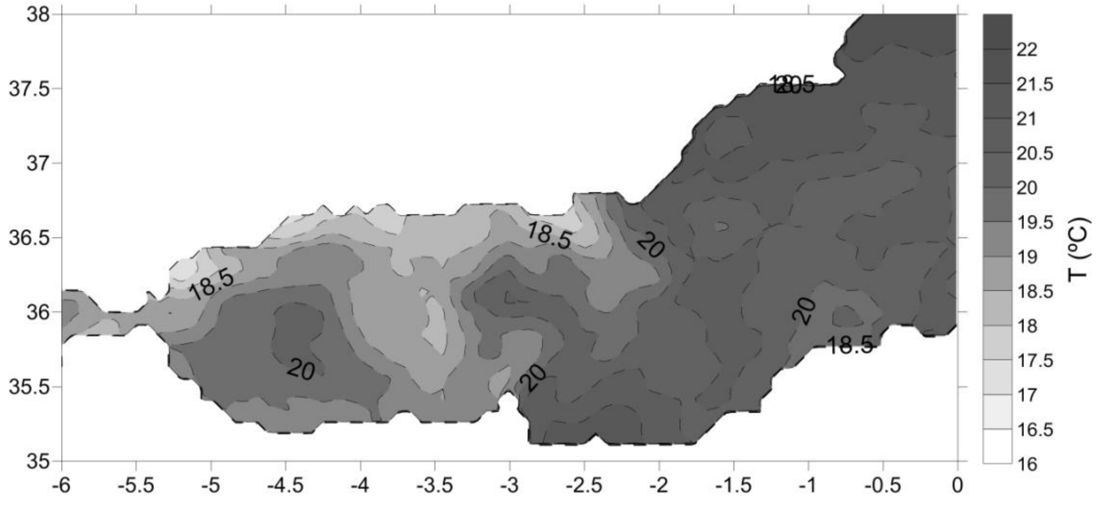

Figure 4 – SST results for June 13, 2009. Remote sensing data with 2 km resolution provided by the Mersea project.

This area is characterized by strong bathymetry gradients associated with Cabo de Gata promontory. This topographic feature is the underwater continuation of Cabo de Capa cape. A detailed analysis of the model results reveals the promontory as an important source of internal wave activity in the Cabo de Gata area. The promontory presence induces a strong vertical velocity perturbing the thermocline in a persistent way. The presence of internal waves can be visualized by looking at the evolution of isotherm lines in space. Model results over the promontory presented isotherm lines with a wave configuration with amplitudes in the order of 10 m. This perturbation of the isotherms was persistent along the entire model simulation. In conclusion, there are persistent vertical periodic movements associated with topographic features (e.g. Cabo de Gata promontory). These vertical movements perturb the isotherms and perturbations are propagated in the density field (internal waves). The signature of the internal waves over the SST tends to be attenuated by the presence of the surface mixed layer where the flow and water properties are homogenized vertically. The SST signatures of oceanic internal waves tend to increase when the wind stress decreases[11]. The SST model results (first layer) do not present the observed anomalies with the exception of Level 5 (Δx~40 m) applied to Morrón de los Genoveses area. This anomaly was associated with the breaking of an internal wave, explained in detail below. However, at a 10 m depth (approximately the thermocline depth) the model 3b and 4b nesting levels presented anomalies similar to the ones observed at the surface. It seems that model overestimated the blocking effect of the surface mixing layer, probably due to lack of horizontal resolution. From the computational effort point of view it was not efficient to simulate the entire area of interest with this spatial resolution.

The model at a 10 m depth presents strong temperature gradients over the Cabo de Gata promontory (Figure 5 – feature highlight by the first arrow counting from left) and an isolated cold water mass (Figure 5 – feature highlighted by the second arrow). The third arrow in Figure 5 points to a cold filament present along the slope originating in the area of strong temperature gradients located along the coastline between Las Negras and Carboneras villages (Figure 3). All temperature features enumerated can be linked to observed SST anomalies (Figure 5).

Over the promontory there are complex and periodic vertical movements that might explain the temperature patterns observed in this area. The SST observations show a detached cold water mass in front of San Jose village. The analysis of model results at the thermocline depth (~10 m) show cold water masses being released in the promontory area in a periodic way and being propagated northeastward. Finally the coastal area located between Negras and Carboneras villages in the model results reveal a strong interaction with internal waves. The consequences of this interaction are strong temperature gradients over the shelf.

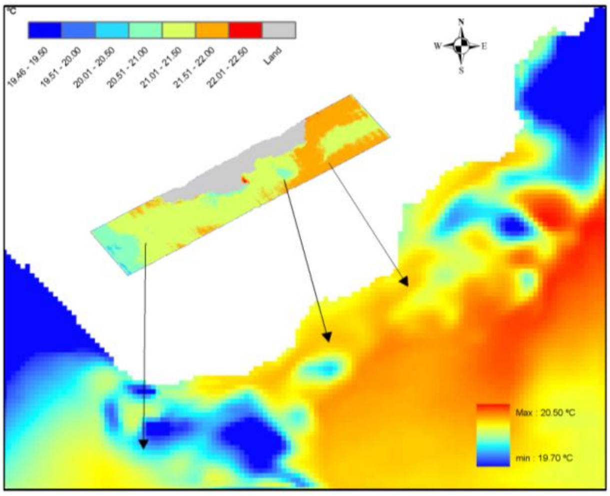

Figure 5 – Model (nesting level 4b) temperature results at a 10 m depth for June 13, 2009 at midnight (black signifies temperature below 19.70ºC). Model results overlapped by a SST image for the Cabo de Gata area. Observed SST anomalies are linked with model temperature gradients at a 10 m depth. From left: first arrow – Cabo de Gata promontory, second arrow – cold lense propagating north-eastward, third arrow – cold filament present along shelf slope in northeast area of the model domain.

A clear negative SST anomaly westward of Morrón de los Genoveses was observed quite restrained to the coast (Figure 6). A detailed analysis of circulation in the hours and days leading up to the SST image taken from a airplane, shows an intense flow that periodically reverses. On June 13, 2009, at midnight, the hydrodynamic model shows a clear westward circulation.

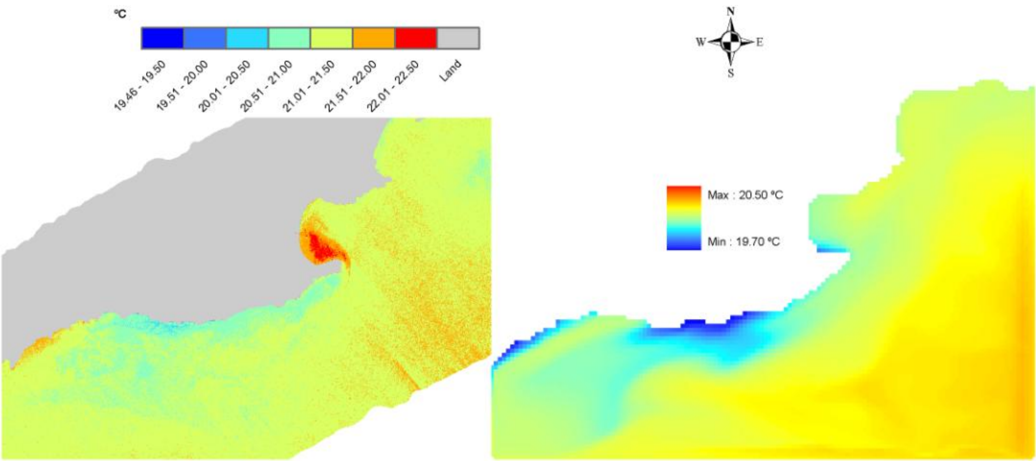

Figure 6 – Left panel details SST anomalies in Cabo de Gata area near Morrón de los Genoveses, right panel – SST models results of nesting level 5. Both panels are for June 13, 2009 at 0:00 hours.

The high resolution model results of SST (nesting level 5b) shows an intense negative anomaly west of Morron de los Genoveses at June 12, 2009 at 22:00 hours reaching the coast from south (Figure 7 - right panel). After reaching the coast the negative anomaly was transported along the coast westward (Figure 6). Based on the model results it was possible to put forward an explanation of the processes behind this negative SST anomaly: an internal wave propagating up slope reaches nesting level 5b south open boundary at 19:00 hours (Figure 7 left panel) and the coastline at 22:00 hours (Figure 7 right panel) dropping the temperature near the coast. This internal wave, besides decreasing the near shore temperature, also induces strong vertical mixing (internal wave breaking). A similar process was described by Pineda[2] in the southern California coast.

The mixing generated a persistent SST anomaly that is transported westward along the coastline by the superficial horizontal currents. The model results had a negative bias of approximately 1ºC. This was related with the underestimation of the heat transport associated with the Catalan Current inducing a general bias of -1ºC in Cabo de Gata area. The temperature gradients were however quite accurate. The difference between the negative anomaly and the off-shore water was approximately ~0.7ºC in the observed data (Figure 6 – left panel) a similar value to the one identified in the numerical models results (Figure 6 – right panel).

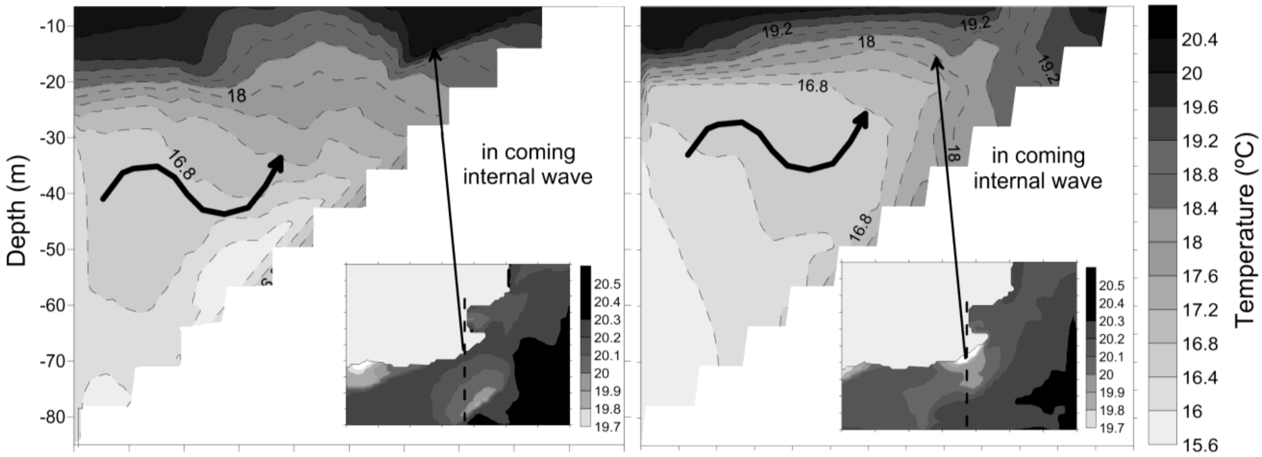

Figure 7 – Normalized temperature model results (nesting level 5b) along a south-north section (2º7'W) : upper panel – June 12, 2009 at 19:00 hours and lower panel – June 12, 2009 at 22:00 hours.

4.2 Nerja – La Herradura

The SST airplane images reveal negative temperature anomalies in Nerja - La Herradura area (Figure 8). Crossing the SST data with the hydrodynamic model results it was explored the hypothesis of anomalies being generated by several SGD's spread around the coast. However, in December 2010 there was no evidence of significant SGD's in the anomalies area. In this campaign only the signature of superficial fresh water discharges was detected. The associated plumes are very small, some few hundred meters, and quite restrained to the coastline. Of the superficial discharges, the only one that can be detected in the SST image of June 13 is the one corresponding to Playa de Maro (Figure 8).

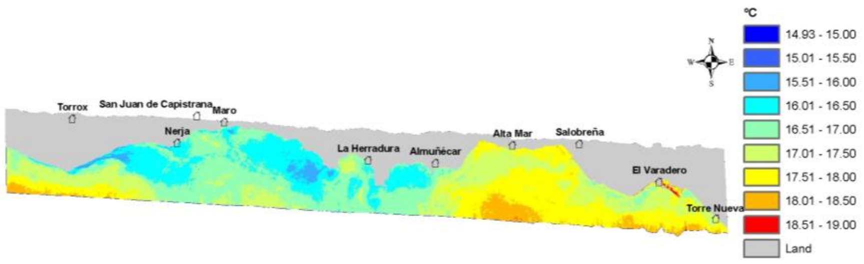

Figure 8 – SST airplane image measured on June 13, 2009 at approximately midnight and main localities near the area of interest.

So what was causing the observed SST anomalies? A similar question was asked for the Cabo de Gata area and the answer was: internal waves. This hypothesis was also tested for the Nerja-La Herradura area. The large scale model used to simulate the western Mediterranean Sea (nesting level 2) shows Gibraltar as a persistent source of internal waves as stated extensively in the literature[4]. In Figure 9 were plotted several instants of vertical velocity at a 20 m depth for June 12 and 13 of 2009. These results show clear pathways of internal waves (or internal tide) in the Alboran Sea. One of these pathways intersects the Nerja – La Herradura coastal area. The results also show a persistent positive vertical (upwelling) velocity in the south boundary of the area of interest on June 12, 2009 at 22:00 hours (Figure 9 - lower left panel). After the upwelling velocity becomes generalized to the all area of interest (Figure 9 - lower right panel - June 13, 2009 at 4:00 hours).

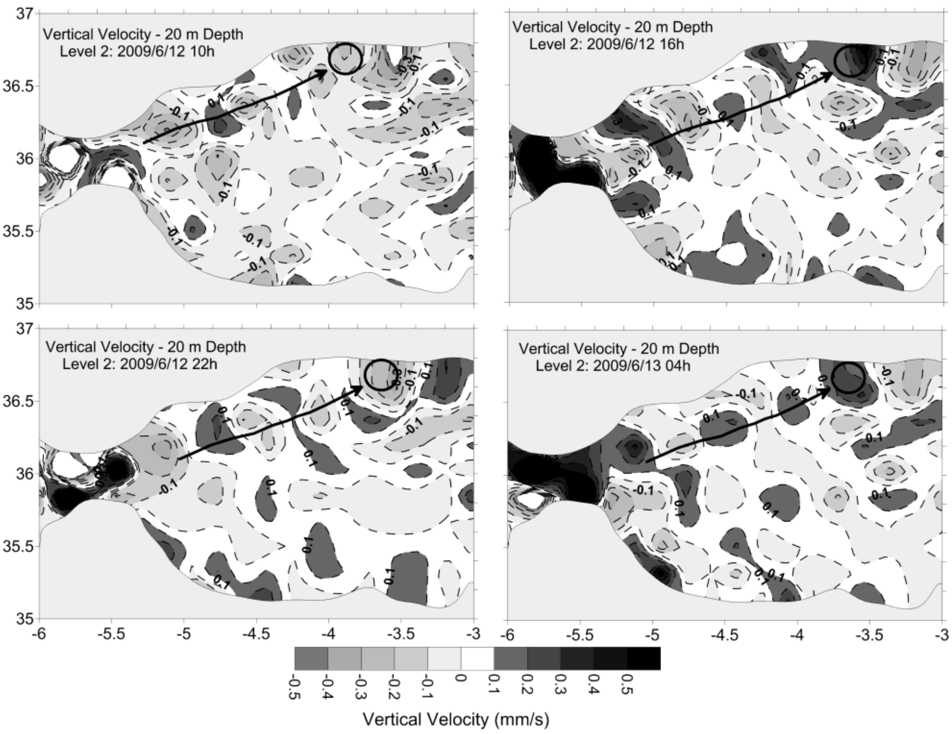

Figure 9 – Model results of vertical velocity at a 20 m depth. This results show the pathway of internal waves (or internal tide) generated in Gibraltar and propagated in the direction of Nerja – La Herradura area.

The large scale SST data presented in Figure 4 for the area of interest for June 13 shows a value of 18 ºC, equal to the highest values measured by the airplane for Nerja - La Herradura area. It is still necessary to explain the origin of values of 16.5-17ºC near the coast from Ponta de Torrox to La Herradura (Figure 8). Considering the size of this area and the salinity anomalies measured in the December 2010 field campaign the fresh water discharges must be discarded as a possible cause.

The SST model results did not present a pattern similar to the one observed. However, the pattern at a 10 m depth (Figure 10 – lower panel) was very similar to the one observed at the surface (Figure 8). This signifies that the model, like in Cabo de Gata, overestimated the blocking effect of the surface mixing layer. At a 10 m depth the model presents a decrease of 1ºC near the coast between Ponta de Torrox and La Herradura (Figure 10) relatively to the offshore temperature of 18ºC. This negative anomaly has its origin in the effect of internal waves. The pathway of these internal waves was easily observed in the vertical velocities model results in 2, 3a and 4a nesting levels. The model results for the vertical velocity at a 10 m depth presents the first signs of a persistent upwelling velocity near the coast at 21:00 hours. The model results presented until midnight (time instant of the airplane image of SST) a persistent upwelling velocity responsible for the negative anomaly of temperature near the coast.

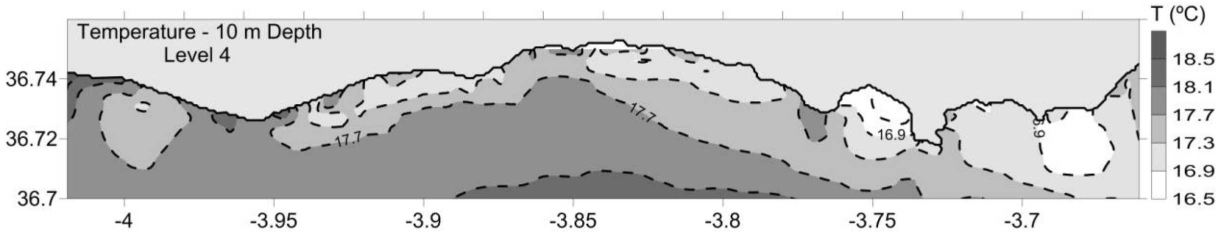

Figure 10 – Model results of temperature at a10 m depth (nesting level 4a – horizontal resolution of ~200 m): June 13, 2009 at 0:00 hours.

5 CONCLUSIONS

The work tested the hypothesis of a connection between observed superficial temperature and salinity SGD's anomalies. Based on the hydrology data and *in situ* data it was possible to conclude that the observed SST anomalies could not be generated by fresh water discharges. This conclusion generated a second goal: suggest an explanation for the origin of the negative anomalies observed in the high resolution SST images obtained on June 13, 2009 for the areas of interest (Nerja/La Herradura and Cabo de Gata). The main conclusion was that the internal tide activity can be responsible for the SST anomalies observed remotely. These internal waves in the areas of interest are mainly tidal driven. In both areas of interest the observed negative anomalies were not related to SGD's. The numerical model was a critical tool to identify the processes responsible for the SST negative anomalies observed remotely.

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