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Internal waves and short-scale distribution patterns of chlorophyll in the Strait of Gibraltar and Alborán Sea

A. Vázquez,[1] S. Flecha,[2] M. Bruno,[3] D. Macías,[4] and G. Navarro[2]

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[1] A selection of ASAR images have been analyzed, together with instantaneous images of surface chlorophyll recorded with MERIS and MODIS, in order to study the relationship between the physical and biological processes associated with internal waves in the Strait of Gibraltar and Alborán Sea. The images show peak levels of chlorophyll at the coastal edges to the north and south of the Camarinal Sill (CS) during the generation of internal waves, and peak levels of chlorophyll associated with the wave fronts as they travel into the Alborán Sea. The images have been compared with *in-situ* data. The results seem to indicate that, during the generation of the internal waves, a suction process takes place by which coastal waters rich in chlorophyll are drawn towards the center of the channel and then accompany the internal waves as they move towards the Alborán Sea. **Citation:** Vázquez, A., S. Flecha, M. Bruno, D. Macías, and G. Navarro (2009), Internal waves and short-scale distribution patterns of chlorophyll in the Strait of Gibraltar and Alborán Sea, *Geophys. Res. Lett.*, *36*, L23601, doi:10.1029/2009GL040959.

1. Introduction

[2] The high amplitude internal waves of the Strait of Gibraltar (Figure 1a) are generated by the interaction of the supercritical flow over the topography of the Strait's principal seabed elevation, the Camarinal Sill (CS), during the phase of tidal outflow (towards the Atlantic). When the flow weakens and becomes sub-critical, the waves are propagated while undergoing a progressive disintegration and this gives rise to a train of internal waves that penetrate into the Alborán Sea [e.g., *Farmer and Armi*, 1988]. Traditionally, the generation of these waves has been associated with periods of spring tides [*Frassetto*, 1964; *Ziegenbein*, 1969; *Farmer and Armi*, 1988], while *La Violette and Lacombe* [1988] and *Watson and Robinson* [1990] were the first to record this internal activity during neap tides. More recent studies [*Vázquez et al.*, 2008] have revealed that these waves are generated when the velocity of the outflow reaches ~ 1 m s^{-1} (before the peak outflow) and they are released when the velocity of the outflow reaches ~ 1 m s^{-1} (after the peak outflow); this leaves the waves trapped for several hours by the flow over the CS: the stronger the outflowing current, the longer they are trapped there. In addition, it has been found that the contribution of the sub-inertial flows in the Strait due to the changes of atmospheric pressure in the western Mediterranean can modify the periods in which these waves are generated. As we know, high pressures in the western Mediterranean intensify the outflows [*Candela et al.*, 1989] and are thus able to activate the generation of internal waves during neap tides; and low pressures over the western basin of the Mediterranean produce a decrease of the outflows and are thus able to inhibit wave generation during spring tides [*Vázquez et al.*, 2008]. One important consequence of the internal waves is the mixing that they induce which can be particularly important for understanding the biogeochemical cycles that take place in the Strait of Gibraltar [*Macías et al.*, 2007a, 2007b]. The first study of the distribution of biogeochemical variables and their relationship to the hydrodynamics of the Strait of Gibraltar was carried out in the CANIGO project [*Echevarría et al.*, 2002]; in this study it was concluded that the processes of mixing due to the generation of internal waves on the CS inject nutrients from the Mediterranean layer to the Atlantic layer; they are transported towards the Mediterranean by advection thus making possible the increased biological productivity and accumulation of biomass in the northeast sector of the strait. However, the time that elapses from the generation of the waves on the CS until their arrival at the eastern limit, around 12 hours, does not seem sufficient to explain the notable increase seen in the concentration of phytoplankton [*Macías et al.*, 2006]. The latest studies on this topic support the hypothesis that a suction process takes coastal waters rich in chlorophyll towards the center of the channel during the generation of the internal waves, and that these enriched waters would move with the train of waves during their propagation eastwards. Considering that after releasing, the background state of vertical shear of current velocity [*Sánchez-Garrido et al.*, 2008] match the wave-induced vertical shear at the internal wave troughs, it is suspected that the transport of the chlorophyll patchiness, following the released internal waves could be aided by the formation of trapped cores inside the trains [*Lamb*, 2003]. On the one hand, the results of a numerical model of coupling between physical and biochemical processes show that the time of residence of the phytoplankton in the Strait is much less than the time necessary to cause an appreciable increase of the population [*Macías et al.*, 2007b]; on the other hand, a study of the composition and nature of the communities of phytoplankton in the strait reveals the existence of chlorophyll nuclei whose characteristics are different from those found in the open sea [*Macías et al.*, 2008]. In the Strait of Gibraltar the surface signals produced by the internal waves consist of a series of rough bands, known as *boiling water*

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[1] Departamento de Física Aplicada II, Universidad de Málaga, Malaga, Spain.

[2] Instituto de Ciencias Marinas de Andalucía, CSIC, Puerto Real, Spain.

[3] Departamento de Física Aplicada, Universidad de Cádiz, Puerto Real, Spain.

[4] Integrative Oceanography Division, Scripps Institution of Oceanography, La Jolla, California, USA.

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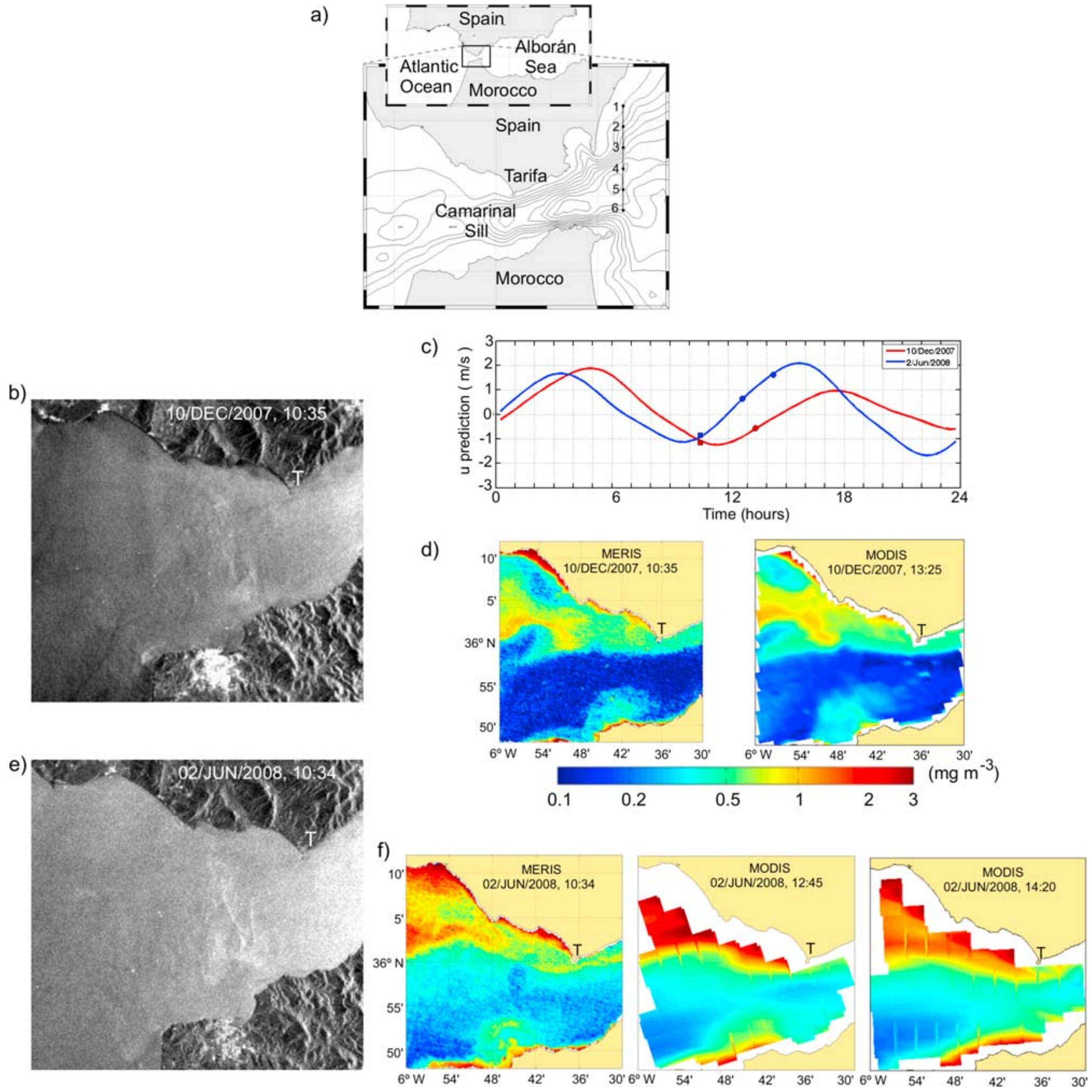

Figure 1. (a) Chart of the Strait of Gibraltar and location of CTD stations. (b) ASAR image on 10 December 2007. (c) Tidal velocity prediction of 10 December 2007 (red) and 2 June 2008 (blue), showing when ASAR and MERIS images (squares) and MODIS (circles) were acquired. (d) Colour images on 10 December 2007. (e) ASAR image on 2 June 2008. (f) Colour images on 2 June 2008.

[*Bruno et al.*, 2002], easily identifiable using synthetic aperture radar systems [*Alpers and La Violette*, 1993; *Brandt et al.*, 1996]. However, the images of surface chlorophyll have not previously been employed in studies of the internal waves in the Strait. This is because, inter alia, the high spatial and temporal variability of this phenomenon requires the employment of instantaneous and not averaged images as is usually done to overcome the problem of cloud coverage characteristic of the study zone. Up to this moment, in only one study, that by *Da Silva et al.* [2002], surface chlorophyll and SAR images were utilized in order to study the relationship between physical and biological processes of internal waves in the Bay of Biscay. In the study presented here, we use a similar methodology to *Da Silva et al.* [2002] to analyze the time-space distribution of surface chlorophyll related with the internal waves generation and propagation in the Strait of Gibraltar and its influence in Alborán Sea and, in addition, the remote sensing results are confirmed by *in-situ* data. The paper is structured in four parts. Following this introduction, there is a description of the material utilized; then the results are presented; and, lastly, there is a discussion of the results.

2. Material and Methods

2.1. Satellite Images

[3] Advanced Synthetic Aperture Radar (ASAR Image Mode) images collected by the ESA's Envisat satellite have been used to evaluate the presence of internal waves in Strait of Gibraltar and Alborán Sea. Together with ASAR images, several full-resolution (300 m) geo-located and atmospherically-corrected (level-2) images with algal pigment index data from the MERIS sensor were downloaded from the Eoli-sa catalogue. In addition, we have used MODIS Level 2 surface chlorophyll images (1 km) from data sets (http://oceancolor.gsfc.nasa.gov/) to obtain several chlorophyll data images for each day. The MODIS chlorophyll images were projected by Matlab Software, in a similar way to the MERIS Algal pigment index. A total of 1337 ASAR images, from 2002 to 2008, have been reviewed; internal waves in the study zone have been detected in 194 of these images. However, the great majority were impossible to analyze jointly with the simultaneous images of surface chlorophyll, due to the presence of clouds in the zone. The ASAR images taken simultaneously with the cloud-free images of chlorophyll have been organized in two groups for their interpretation. In one group, the images in which the internal waves are in their generation phase are presented, and in the other, those in which the waves are being propagated in the Alborán Sea. For detailed information about satellite images see the auxiliary material.[1]

2.2. In-Situ Data

[4] The information obtained from the remote sensing images, has been compared with *in situ* data collected with CTD during the GIBRALTAR 08 campaign, on board the B.O. Sarmiento de Gamboa. The data correspond to a transect of 6 stations distributed from North to South at the eastern exit of the Strait, carried out on 30 September 2008 (Figure 1a). The fluorescence data provided by the CTD in the vertical profiles have been converted into units of Chlorophyll-a ($r^2 = 0.68$, $p < 0.01$) using 256 samples from bottles, in which the quantity of Chlorophyll present was determined following *Macías et al.* [2008].

2.3. Prediction of Tidal Currents

[5] The processes of generation and release of internal waves in the CS depend on the state of the tidal currents on the sill. It is therefore essential to predict the currents at the CS in order to know the conditions in which the waves generated can be found. These predictions have been carried out according to the method explained by *Vázquez et al.* [2006].

3. Results

3.1. Generation of the Internal Waves

[6] In the ASAR image corresponding to 10 December 2007 at 10:35 hours UTC (Figure 1b), the presence of rougher bands on the surface of the sea over the CS can be clearly observed, identified by the higher radar image intensity. The prediction of tidal currents (Figure 1c) indicates that, at the time when the ASAR image was taken, the tide was flowing out towards the Atlantic Ocean, at a velocity of $\sim$1 m s^{-1}. The presence of sea surface roughness bands in this zone, together with the information from the prediction of current, reveals that the internal waves were just beginning to be generated at this point in time. In the simultaneous MERIS image (Figure 1d), it can be detected that the waters off the northern coastline of the Strait of Gibraltar have a greater concentration of chlorophyll (>0.5 mg m^{-3}), especially in the zone of Trafalgar and with a branch, in a northeast to southwest direction, that reaches almost as far south as the CS. The center and south of the channel of the Strait is poorer in chlorophyll ($\approx$0.1 mg m^{-3}), but a body of water relatively richer in chlorophyll is notable to the south of the CS. Three hours later the MODIS image was taken; the structures previously described continue to be observed in this image although some advection of chlorophyll has taken place on the southern side of the channel while in the northern side it has remained almost stationary. At the time of the images upper layer current is westward (see Figure 1c) so that advection in that direction is expected to occur in the central zone of the channel. However, westward advection will be more notable on the southern side where a very narrow continental shelf exposes clearly the water masses near the coastal margin to the central channel hydrodynamics. By the contrary, a wider continental shelf on the northern side seems to prevent those waters from the westward displacement.

[7] On 2 June 2008 at 10:34 UTC we were able to capture another instance of internal wave generation in the ASAR image (Figure 1e). Again bands of rougher water can be seen on the surface of the sea over the sill. According to the prediction of tidal current in the top layer over the CS, water is flowing towards the Atlantic Ocean at a velocity of $\sim$1 m s^{-1} after the peak outflow (Figure 1c). According to the empirical method presented by *Vázquez et al.* [2008], on this occasion the waves should have begun to be generated at about 09.00 UTC, and at approximately 10.30 UTC, the time when the ASAR and MERIS images were taken, they should have been arrested by the flow over sill. In the MERIS image (Figure 1f), it is again possible to observe a pattern clearly similar to that seen on 10 December 2007, characterized by the presence of waters rich in chlorophyll in the north of the channel (up to 36° N) with a "tongue" of higher concentration in the NW-SE direction, and waters poor in chlorophyll in the southern half of the strait, apart from a nucleus of water of higher chlorophyll content off the coastline to the south of the CS. For that day two MODIS images free of clouds are available, taken two and four hours later (Figure 1c); in these, it can be observed that the waters close to the north and south coasts show an increased concentration of chlorophyll. In the first of these, taken at 12:45 UTC, shortly after the change of current from outflow to inflow, it can also be observed that the nucleus of waters richer in chlorophyll detected off the south coast has increased its area and has been displaced eastwards. Equally, off the north coast, the area of enriched waters has extended southwards to below 36° N, and the waters poor in

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL040959.

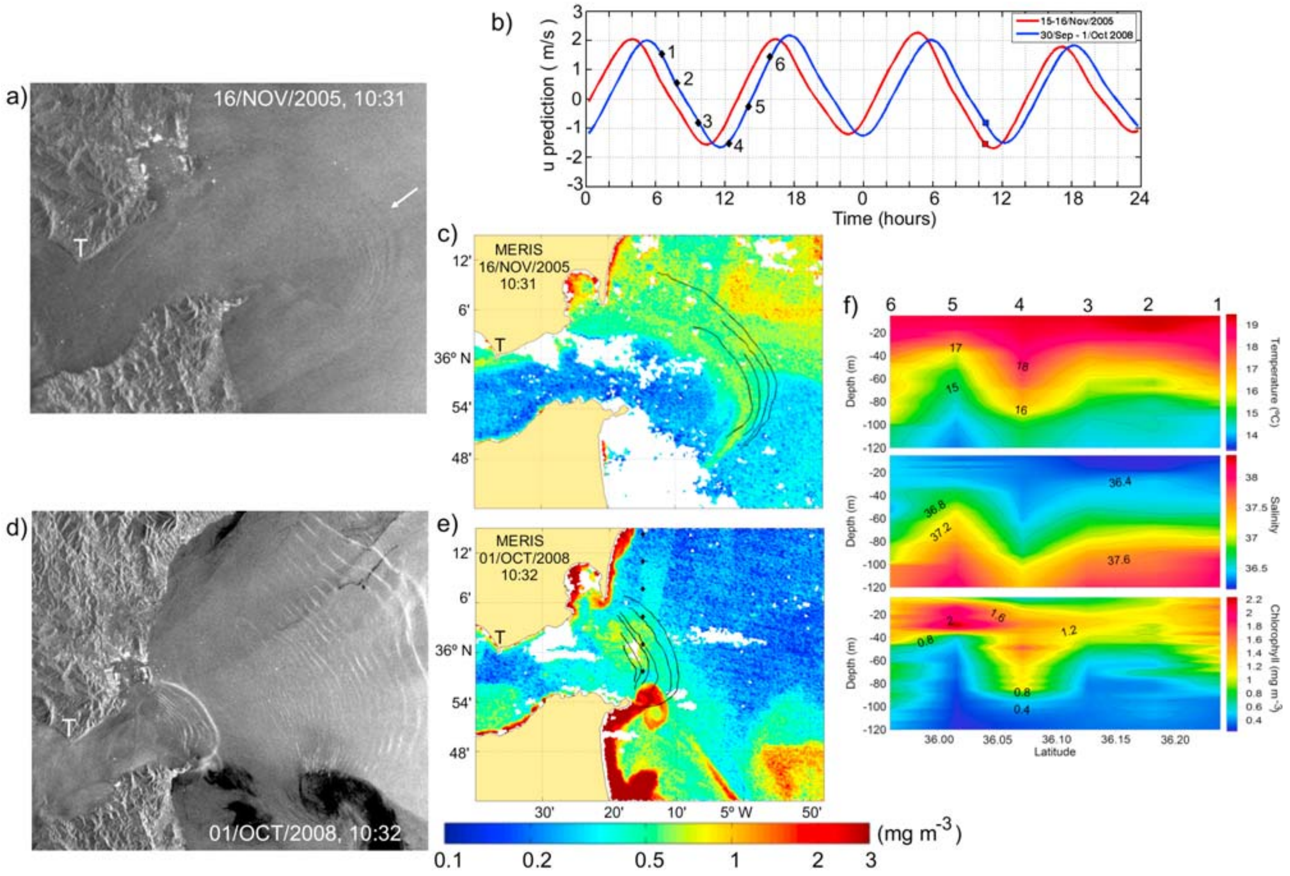

Figure 2. (a) ASAR image on 16 November 2005. Arrow indicates the train of internal waves. (b) Tidal velocity prediction of 15–16 November 2005 (red) and 30 September–1 October 2008 (blue), showing when ASAR and MERIS images (squares) and six CTD cast (black circles and numbers) were taken. (c) Colour image on 16 September 2005. (d) ASAR image on 1 October 2008. (e) Colour image on 1 October 2008. (f) CTD sections along line shown in Figure 1a. Numbers on the top indicate the CTD cast.

chlorophyll are subjected to a "squeezing" effect that leaves them reduced to the central line of the channel between the CS and Tarifa. In the image taken at 14:20, shortly before the peak inflow, this squeezing effect is more noticeable and is displaced geographically towards the east; water with a relatively high content of chlorophyll is found at the latitude of Tarifa, separating two nuclei of water poor in chlorophyll on either side.

3.2. Propagation of the Internal Waves

[8] The ASAR image of 16 November 2005 (Figure 2a) was taken at 10:31 UTC, practically coinciding with the peak tidal outflow (Figure 2b). A train of internal waves penetrating into the Alborán Sea can be observed in this image (Figure 2a). Furthermore, in the simultaneous image of surface chlorophyll (Figure 2c), an increase of chlorophyll is observed in the Alborán Sea, which clearly matches the position of the train of internal waves. The last ASAR image was captured on 1 October 2008 at 10:32 UTC (Figure 2d), during the phase of tidal current outflow over the CS (Figure 2b). In this image it can be seen that practically all of the northwestern part of the Alborán Sea is occupied by internal waves grouped in two wave trains. In the simultaneous MERIS image (Figure 2e), it can again be observed that there is an increase of chlorophyll associated with the wave train that is situated at the eastern exit of the Strait. SST images (not shown) indicate that the Atlantic jet was deflected towards the south-east, so it should be expected that an important part of the chlorophyll coming with the internal waves could be drawn out by the Atlantic jet occasioning a lack of chlorophyll along the propagation direction of internal waves trains into the Alboran Sea.

4. Discussion

[9] The two ASAR images, corresponding to the phase when internal waves of great amplitude and short period are generated over the CS (Figure 1), were captured during the tidal outflow with a current velocity of $\sim$1 m s^{-1}. However, the first was taken before the peak outflow, while the second was taken after. This indicates that the ASAR images, and those of surface chlorophyll, of 10 December at 10:35 UTC, show the patterns of surface water roughness and chlorophyll concentration at the moment when the internal waves are generated. In the light of the prediction of currents, these waves should be arrested by the flow until it again reaches the velocity of $\sim$1 m s^{-1}, after the peak outflow, which occurred approximately two and a half hours later. The waves are generated when the flow over the CS becomes critical; that is, when the average speed of outflow towards

the Atlantic Ocean matches the velocity of the hydraulic jump that is trying to propagate itself towards the Mediterranean Sea. While the average velocity of the outflow exceeds 1 m s^{-1} (supercritical flow), the waves will remain arrested over the sill; the release will take place once this velocity decreases, when the flow becomes sub-critical. However, at first, the propagation of the waves towards the Mediterranean Sea occurs very slowly since, although the flow over the CS is sub-critical, the flow is on average in the direction opposite to that of propagation of the waves; and as the outflow weakens and changes its direction, becoming an inflow, the speed of propagation of the waves increases. This explains why the distribution of surface chlorophyll remains practically unaltered between the MERIS and MODIS images of 10 December. The MODIS image was taken at 13:25 UTC, shortly after the release of the waves; at that moment, the tidal current has still not changed its direction and remains in the outflow phase, with a velocity of ~ -0.5 m s^{-1}. Therefore, although the waves would have been released, they would have traveled only a relatively short distance at the time of the image. However, in the images of surface chlorophyll of June, more evolution in the patterns of distribution can be observed. As has been seen, the ASAR and MERIS images were taken at the time of release of the waves, after they had remained arrested by the flow for some two hours. During this period, the waves gain energy from the average tidal flow and increase their amplitude [*Vázquez et al.*, 2006]; this is probably the reason why the waves can be observed better in Figure 1e than in Figure 1b. The two MODIS images were taken somewhat later, during the phase of tidal inflow, when the flow direction is towards the Mediterranean Sea. By this time the velocity of propagation of the waves is already notable $\sim$1 m s^{-1} [*Sánchez-Garrido et al.*, 2008] and the position of the squeezed minimum area of chlorophyll coincides with the position of the internal waves (Figure 1e).This relative peak of surface chlorophyll accompanies the waves in their propagation until they reach the Alborán Sea, as can be observed in the images of Figures 2c and 2e, which thus corroborate the *in-situ* data. In the sections of temperature, salinity and chlorophyll, the passing of an internal wave can be clearly observed; the trough of the wave is at 36.07° N and its crest is at 36.00° N (Figure 2f). It can be observed that, on the crest of the internal wave, there is an increase of the chlorophyll concentration, and the concentration peak becomes uplifted, as suggested by *Da Silva et al.* [2002]. The crest of the internal wave was detected at Station 5 after the peak tidal outflow, which is in accordance with the estimated time of arrival of the waves that are generated during the tidal outflow of the previous cycle, in this case that corresponding to 30 September ~00:00 UTC, the intensity of which was sufficient for the generation of the wave. The distribution of surface chlorophyll during the phase of generation and propagation of the internal waves seems to indicate that, during the generation, waters rich in chlorophyll, which are characteristic of the coastal edges, are advected towards the center of the channel. This process of suction is clearly evident in the color images corresponding to the phases of wave generation in Figure 2c, in which a band of high concentration of chlorophyll can be clearly observed; this band extends from close to Cape Trafalgar as far as the area of the sill itself. The water drawn from the coastal areas is retained in the zones of surface convergence produced by the velocity field of the internal waves between their troughs and crests in such a way that, when the waves are released, the water of coastal origin travels with them as they propagate towards the Alborán Sea. The convergence from the coast towards the center of the channel during the generation of the internal waves over the CS may occur because the waves are produced during the more intense outflows, in which the flow in the upper layer, which is customarily towards the Mediterranean Sea, may be reversed, whereas from Tarifa this flow of the upper layer is always in the eastwards direction [*García-Lafuente et al.*, 2000]. In these situations a divergence takes place in the longitudinal axis of the Strait that must be compensated with the supply of deeper coastal waters. Subsequently, when the flow over the sill turns eastward those coastal waters move in the flow direction along with the internal waves. To the light of the results, it seems evident that, as a consequence of the physical mechanism of generation and propagation of the internal waves of the Strait of Gibraltar, the waters of the Alborán Sea are enriched with chlorophyll; this sea is a zone characterized by complex dynamic processes such as the entry of the Atlantic jet, the generation of coastal blooms, and the formation of cyclonic and anti-cyclonic eddies. Studies of these patterns of circulation, and the biological response to them, must therefore consider their relationship with the wave-related processes of the Strait, which take place in the form of regular pulses.

[10] As a final reflection on the findings of this study, it should be emphasized that chlorophyll values estimated from satellite images must be treated with caution as representative values for the zone because, as the *in situ* data show, the highest content of chlorophyll is found in the subsurface rather than in the surface layer of water. Therefore, when observing an image of surface chlorophyll, it is necessary to understand what is happening a few meters below; this means recognizing that the actual chlorophyll concentrations, and consequently the estimates of biological production of the study zone, will always be higher than those inferred from the information supplied by images of surface chlorophyll.

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M. Bruno, Departamento de Física Aplicada, Universidad de Cádiz, E-11510 Puerto Real, Spain.

S. Flecha and G. Navarro, Instituto de Ciencias Marinas de Andalucía, CSIC, E-11510 Puerto Real, Spain.

D. Macías, Integrative Oceanography Division, Scripps Institution of Oceanography, La Jolla, CA 92037, USA.

A. Vázquez, Departamento de Física Aplicada II, Universidad de Málaga, E-29071 Málaga, Spain. (agueda.vazquez@uca.es)