Multi-sensor survey of seasonal variability in coastal eddy and internal wave signatures in the north-eastern Black Sea

M. I. Mityagina; O. Y. Lavrova; S. S. Karimova

* Space Research Institute of the Russian Academy of Sciences, Moscow, Russia

Online publication date: 28 September 2010


To link to this Article: DOI: 10.1080/01431161.2010.485151
URL: http://dx.doi.org/10.1080/01431161.2010.485151

Please scroll down for article.
Multi-sensor survey of seasonal variability in coastal eddy and internal wave signatures in the north-eastern Black Sea

M. I. MITYAGINA*, O. Y. LAVROVA and S. S. KARIMOVA
Space Research Institute of the Russian Academy of Sciences, Moscow, Russia

In this paper the remote sensing satellite sensor data (obtained by Envisat Advanced Synthetic Aperture Radar (ASAR), Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS), and National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) instruments) is used to study coastal dynamics of the north-eastern Black Sea. Occurrence, evolution and drift of small-scale eddies in coastal waters are investigated. Seasonal variability of their manifestations is established.

Instances of surface manifestations of non-tidal internal waves (IW) are discovered. The main finding was that practically all cases of IW manifestations were observed in the vicinity of mesoscale sea eddy structures or hydrological fronts. The joint analysis of data from different sensors was performed to reveal specific conditions leading to the intensification of wave processes and to their manifestation in radar imagery as well as to determine possible sources of the IW generation.

1. Introduction

The importance of the Black Sea extends far beyond its regional role. The sea’s marine environment acts as a laboratory for investigating processes common to different areas of the world’s oceans. There is a large body of research work dealing with different aspects of Black Sea circulation and dynamics (Neumann 1942, Stanev 1990, Oguz et al. 1993, Blokhina and Afanasyev 2002, Poulain et al. 2005).

The investigation of mesoscale features in coastal zones is important for understanding local mechanisms of mixing and circulation processes. To a large extent, these mechanisms determine the ecological, hydrodynamic and meteorological state of coastal zones, whose constant monitoring is vital for densely populated regions.

It is of interest to detect, observe and explore mesoscale features (in particular vortex structures and internal waves of a non-tidal origin) and to indicate applicable methods and instruments. In this paper the remote sensing satellite sensor data (obtained by Envisat Advanced Synthetic Aperture Radar (ASAR), Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS), and National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) instruments) is used to study coastal dynamics of the north-eastern Black Sea. Data from multiple remote sensors are analysed together to better understand coastal water circulation and to identify and study patterns that are not recognizable by individual sensors.

One of the results presented in this paper concerns the occurrence, evolution and drift of vortical structures. Specifically, via the analysis of radar imagery the existence of small scale eddies is discovered. They were previously not detectable by traditional infrared (IR)

*Corresponding author. Email: mityag@mx.iki.rssi.ru
and optical methods. It is shown how radar imagery could be combined with data from optical and IR remote sensors to reconstruct a more complex structure of coastal circulation. A complete lifecycle of near-shore vortical structures is studied on the base of satellite sensor data and a seasonal variability of their manifestations is established.

Small-scale spiral eddies are a distinct sea surface pattern. Satellite observations of vortical structures of this type were reported in different areas of the World Ocean. They are found both in coastal areas and in the open ocean (Stevenson 1998, Munk et al. 2000, DiGiacomo and Holt 2001, Eldevik and Dysthe 2002). Our work provides further evidence of small-scale eddies being a necessary element of coastal water circulation.

Eddies become visible in radar images due to numerous bands of slicks of surfactant films which get entrained in the eddy motion. Biogenic films are very sensitive to surface currents and usually follow a local circulation pattern. Water dynamics forces biogenic films to accumulate along the flow lines of surface currents. Since the films affect the backscattering of microwaves, these structures become visible in the synthetic aperture radar (SAR) imagery which allows monitoring of water dynamic processes via their surface manifestations. By taking advantage of this two-stage process, we are able to improve and extend the information inferred from satellite imagery of coastal zones. In particular, due to the presence of surfactant films, SARs are capable of registering eddy structures (Alpers and Hühnerfuss 1989, Johannessen et al. 1996, Gade 2006).

Our further investigation lead to discovery of surface manifestations of non-tidal internal waves (IW) in the Black Sea coastal waters. The main finding is that practically all cases of IW manifestations are observed in the vicinities of mesoscale sea eddy structures or hydrological fronts. The experimental evidence of IW caused by vertical structures is obtained.

Internal waves are known to strongly affect processes in the ocean. Motions induced by IW transpierce the whole body of ocean water and play a particularly important role in the processes near the surface. That is why investigation of IW, mechanisms of their generation, development, propagation and decay has always been a focus of research.

SAR imagery is widely used for investigation of surface manifestations of IW which are visualized in SAR images via a reconstruction of the surface wave spectrum. They are displayed in radar images of ocean surface as alternating bands of enhanced and attenuated backscattering. This is due to modulation of the small-scale surface wave component by variable currents induced by IW in the near-surface layer. There is a number of research publications based on SAR observations of IW in various areas of the World Ocean (Alpers 1985, Liu et al. 1985, Thompson 1988, Ermakov et al. 1998). An atlas of surface manifestations of IW has been created and is maintained (Jackson and Apel 2002), presently comprising over 300 instances of IW patterns from 54 regions of the world. However, most observations were of IW generated by tidal currents in shelf zones. They are produced by tidal currents flowing perpendicular to the local bathymetry and are regularly generated in well known locations.

Meantime, information on IW surface manifestations in non-tidal seas is scarce. The Black Sea, being of relatively small size and semi-closed, can be regarded as a non-tidal sea, that is having no internal tides and associated short-period IW. Shallow and narrow Bosphorus, Dardanelle and Gibraltar Straits do not permit oceanic tidal waves to penetrate into the Black Sea. Nevertheless contact measurements establish the existence of rather intense IW in this area (Ivanov and Serebryany 1985, Goryachkin et al. 1990, Vlasenko et al. 1997). Thus, it is of interest to investigate the IW of this kind using satellite observations.
2. Multi-sensor technique

During 2006–2007, a satellite monitoring of the north-eastern Black Sea was conducted annually during the months of April to October. Over this period, images taken by ASAR on all passes of Envisat satellite over the north-eastern part of the Black Sea (time intervals of 12 or 72 h) were obtained and processed. The basic radar data are complemented by other satellite information on the condition of the sea surface, such as sea surface temperature, suspended matter and chlorophyll-a maps, mesoscale water dynamics charts (NOAA AVHRR, Terra/Aqua MODIS). This allows us to systematize the data and draw some conclusions on dynamic processes in the coastal waters.

Our approach to water dynamics study is based on the following:

- Continuous data inflow is maintained from satellite sensors operating in microwave visual and infrared ranges on board of Envisat, Terra and Aqua, NOAA and Quick Scatterometer (QuikSCAT) satellites.
- Satellite sensor data passes preliminary processing, georeferencing and cartographic mapping. Data from different spectral channels is transformed into multizonal composites.
- Every SAR image is visually analysed in order to detect dynamical structures belonging to the classes of spiral eddies, IW manifestations, fronts, etc.
- Thematic processing of visual and infrared data from Terra/Aqua MODIS, Envisat MERIS and NOAA AVHRR includes recognition and classification of water bodies, mapping sea surface temperature (SST), chlorophyll-a concentration, water mass motion, etc.
- Near-surface wind speed is retrieved using QuikSCAT scatterometer data.

3. General circulation features of the Black Sea

The basic circulation in the Black Sea is characterized by a strong cyclonic basin-wide current along the shore which is referred to as the Rim Current (Stanev 1990, Oguz et al. 1993). This current is highly hydrodynamically unstable and consists of a system of moving mesoscale rings and eddies (Oguz et al. 1992, Zatsepin et al. 2002).

The intensity of the Rim Current is modulated by the atmospheric circulation. As a result of atmospheric forcing the circulation of the Rim Current is more clearly defined and intense during winter than in summer; whereas in summer eddy activity is more pronounced at the very different scales (Sur and Ilyin 1997, Shcherbak et al. 2008). In summer, as a rule, closely packed vortical structures fill the zone between the shoreline and the main jet of the Rim Current. Some of them are associated with the meandering Rim Current, while others are produced by direct and non-direct impact of wind and buoyancy fluxes. In some cases, for example, in the north-eastern Black Sea, mesoscale eddies can interrupt the Rim Current locally, which results in a substantial cross-shelf transport (Zatsepin et al. 2003, Korotaev et al. 2003).

The trajectory of the Rim Current can be observed in satellite sensor data during winter and spring months, however during the summer eddy variability is so intense that the Rim Current is barely visible. The typical pattern of the Black Sea surface water circulation in cold season is fairly well represented by the SST map derived from AVHRR/NOAA data acquired in February of 2008 shown in figure 1(a). As shown in the image, the Rim Current goes just along the coastline and very close to it. A water leaving radiance (WLR) map derived from Aqua MODIS data taken in June 2006 is...
shown in figure 1(b). This map shows multiple mesoscale near-shore eddies. The eddy variability is so large that it masks the Rim Current such that it can only be defined in terms of statistically computed transport. The dark line schematically shows the estimated position of the Rim Current. So, the most obvious difference between the wintertime and summertime schemes is that in summer there are a great deal of vortical structures in the peripheral part of the sea in the close vicinity of the coastline.

Satellite observations of mesoscale vortical activity in the north-eastern part of the Black Sea have been usually carried out by means of IR or optical sensors (Sur and Ilyin 1997, Ginzburg et al. 2002). Spatial resolution of these images makes it possible to study only eddy structures of about 30 km or larger in size and only in cloudless conditions. These observation methods are only capable of revealing large-scale and mesoscale meanders, anti-cyclonic eddies, pinched off eddies, and vortex dipoles.

The generation and evolution of vortical features of smaller spatial scale and short temporal scale superimposed on the general alongshore flow is practically impossible to monitor by these methods.

4. Small-scale eddies in coastal waters

Our observations over many years indicate that the use of ASAR data considerably extends the possibilities of remote sensing detection and examination of vortex structures of small sizes. SAR instruments have an advantage over IR and optical sensors since they can provide data under cloudy conditions and during darkness. The spatial resolution of SAR instruments is very high - up to \(30 \times 30\) m. Adding SAR images to our datasets allowed the detection of intense small-scale vortex structures (considerably smaller than those mentioned above).

Many small-scale eddies were observed in radar images near the coastal line when the Rim Current slackens. They have sizes of several kilometres, while peripheral ones may be even smaller. Usually, such eddies are spiral in shape and these eddies are mostly cyclonic. Some examples of small-scale spiral eddies detected in radar images of the north-eastern Black Sea are shown in figure 2. These vortex structures are too small to be detected by optical or IR sensors and researchers were previously unaware of their presence in the Black Sea area.
ASAR data from all passes of Envisat satellite over the region during the monitoring period allowed to determine the size, rotation direction and centre coordinates for each observed small-scale eddy structure. All detected small-scale spiral eddies were plotted on a map shown in figure 3(a). Of course, the coastal ocean eddy field is densely populated across a broadband range of spatial scales, but since our attention was focused on the small-scale eddies only the observed meso- and large-scale ones are not shown in here. This graphical representation clearly displays the seasonal variability of small-scale spiral eddies in coastal waters.

These eddies can be naturally divided in two separate groups. Black eddies come from the data obtained in relatively cold periods - earlier than mid-May and later than mid-September. Meanwhile, spiral white eddies occur during warm summer periods. It is easy to see that these groups of eddies are separated by the conventional core line of the Rim Current depicted by dotted line in figure 3(a). It implies that during the warm season small-scale eddies are generated between the coast and the Rim Current, while during the cold season they are located at the seaward side of the Rim Current.

Moreover, additional distinctions between these two types of eddies were found. In warm seasons, mostly small-scale (2–6 km in diameter) solitary eddies are observed (see figure 2(a)–(d)). These are predominantly cyclonic and quasi-two-dimensional structures which are located in shallow waters in the close vicinity of the coastline and have short lifetimes. We believe that the direct and non-direct impact of wind plays an
important role in the eddy formation during the warm season. Eddies of this type can only be seen in radar images and are not found in optical data.

In the cold season eddies are found to accumulate in clusters with individual sizes of 4–32 km. These clusters are located in deep waters about 30 km off the coastline at the bounds of the Rim Current. Examples of ‘cold season eddies’ are shown in figure 2(e)–(g). Both cyclonic and anti-cyclonic eddies with longer lifetimes can also be observed - they provide horizontal as well as vertical mixing of water. We believe that these eddies are generated by Rim Current meandering or breaking of large-scale eddies. These eddy clusters can be seen in both radar and optical data, however only radar data allows the identification of individual eddies and their fine structure to be revealed. The size distributions of small-scale spiral eddies observed in warm and cold seasons, respectively, are presented in figure 3(b) and (c).

5. Eddy dipoles

There is a particular interest in the dipolar or quasi-dipolar eddies (so-called mushroom-like flows). These are spatial quasi-symmetric structures combining a narrow jet with a pair of vortices of opposite signs (Fedorov and Ginzburg 1992, Voropayev and Afanasyev 1994).
Eddy dipoles occur due to local short-time momentum actions onto the surface or near-surface layer of water, induced by local sources of kinetic energy of different origin. Such structures can assure a very effective mechanism for horizontal mixing of sea water. Because of their self-propelling motion, they can transport substances such as salt, heat and biological constituents through large distances. So the eddy dipoles can play an important role in exchange between shelf and deep-sea water. Dynamic vortex structures of this kind are regularly observed in the north-eastern part of the Black Sea (Lavrova et al. 2008). Well-developed eddy dipoles may be distinctly visible in IR and optical data under cloudless conditions. In remotely sensed optical and IR images these structures are only visible when there is a temperature contrast on the surface or some natural tracer. In radar images, eddy dipoles are manifested due to surface roughness contrasts (that are best visible at the edges).

Previously, satellite observations of vortex structures in the north-eastern part of the Black Sea have been performed using IR or optical data, together with in situ measurements. All previous publications regarding similar vortex structures only consider dipoles of several hundred kilometres in size (Ginzburg et al. 2002). Our research shows that the use of radar imagery together with other methods of remote sensing allows us to:

- observe eddy dipoles of significantly smaller size (typically, several kilometres);
- observe early stages of emergence and development of eddy dipoles (before they are visible in IR and optical imagery); and
- observe the fine structure of surface currents induced by a dipole.

We will illustrate this herein.

An eddy dipole is distinctly visible in MODIS images acquired on 20 June (figure 4). It is easy to notice the presence of mushroom-like structures, similar in location and size, in the SST (figure 4(d)) and WLR (figure 4(e)) charts derived from NOAA AVHRR and Aqua MODIS data.

Two ASAR Envisat images, revealing the development of an eddy dipole are shown in figure 4(a) and figure 4(b). These images were acquired a day before (on 19 June) on two successive passes of the satellite within 11 h from each other. Figure 4(a) reveals a nascent eddy dipole 66 km in width and 62 km in length. The same dipole pictured in figure 4(b) grew to a size of 92 km (width) by 78 km (length) and its axis slightly displaced clockwise. Figure 4(c) graphically shows how eddies are moving and developing.

A packet of IW is observed at the edge of the anticyclonic part of an eddy dipole (figure 4(f)). The packet contains six IW with average wavelength of 175 m. Surface manifestations of IW of non-tidal origin detected in ASAR images will be discussed below.

6. Surface manifestations of non-tidal IW

Mesoscale eddies and eddy dipoles are common features for the region of interest (Lavrova et al. 2008). Nevertheless, manifestations of IW on the sea surface generated in the vicinity of these structures can rarely be seen.

Seven instances of IW manifestations in ASAR images of north-eastern Black Sea were identified during monitoring campaigns of 2006–2007, six of which were in 2006. The main characteristics of IW revealed from radar imagery are presented in table 1. Figure 5 presents fragments of SST charts retrieved from NOAA AVHRR data taken...
at relatively close times to the moments of ASAR images acquisition. Asterisks mark location of IW packets. Practically all these IW are located close to a cold eddy structure or a cold hydrological front.

Let us consider in more detail the Envisat ASAR image (figure 6(b)) acquired on 13 June 2006, 7:40 Coordinated Universal Time (UTC) at a pixel resolution of 12.5 m together with a SST chart (figure 6(a)) based on NOAA AVHRR data obtained 17 min after the radar imaging. The SST chart depicts a decaying large-scale eddy. Dark bands distinctly visible in the lower part of the ASAR image correspond to the outer boundary of a cyclonic eddy viewed in the SST chart. In the ASAR image, the boundary is visible due to filamentary biogenic films accumulated in convergence zones of the surface water layer. The IW packet is located close to the area of high contrast. This packet consists of over 20 waves with an average length of 140 m. IW propagate seaward at an angle to the shore and their fronts are parallel to the dipole jet. Most probably, IW occur as a result of oscillations of the dipole jet.

To explain the effect the analysis was carried out of vertical profiles of sea water temperature and buoyancy frequency taken from research vessel in situ measurements. It was found that IW detected in ASAR images were generated during periods when the peak of buoyancy frequency profile was very sharp and located at a shallow depth. Figure 7 gives profiles of temperature and buoyancy frequency calculated from measurements at the isobath 2000 m at which surface IW manifestations dated 13
June 2006 and 19 June 2006 are detected. It is evident that the buoyancy frequency peak is very sharp and located at a depth of about 5 m.

The sharp and shallow pycnocline conditions facilitate the emergence of internal solitons as well as the enlargement of near-surface currents associated with the

Table 1. Main characteristics of internal waves retrieved from Envisat ASAR imagery.

<table>
<thead>
<tr>
<th>Date and time (UTC)</th>
<th>Coordinates of packet centre</th>
<th>Leading wave crest length (m)</th>
<th>Depth (m)</th>
<th>Packet length (m)</th>
<th>Maximum wave length (m)</th>
<th>Number of waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>03 June 2006, 07:54</td>
<td>44° 53' 16'' N, 36° 47' 22'' E</td>
<td>18 300</td>
<td>100</td>
<td>1100</td>
<td>500</td>
<td>4</td>
</tr>
<tr>
<td>13 June 2006, 07:40</td>
<td>43° 43' 02'' N, 38° 14' 11'' E</td>
<td>7100</td>
<td>2000</td>
<td>3260</td>
<td>170</td>
<td>21</td>
</tr>
<tr>
<td>16 June 2006, 19:05</td>
<td>44° 38' 01'' N, 37° 51' 12'' E</td>
<td>7200</td>
<td>50</td>
<td>814</td>
<td>285</td>
<td>5</td>
</tr>
<tr>
<td>19 June 2006, 19:10</td>
<td>44° 13' 56'' N, 37° 34' 46'' E</td>
<td>5600</td>
<td>2000</td>
<td>1300</td>
<td>220</td>
<td>6</td>
</tr>
<tr>
<td>02 July 2006, 07:43</td>
<td>44° 12' 24'' N, 37° 28' 52'' E</td>
<td>13 800</td>
<td>1800</td>
<td>1057</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td>11 July 2006, 19:19</td>
<td>44° 50' 46'' N, 36° 22' 58'' E</td>
<td>13 250</td>
<td>50</td>
<td>4593</td>
<td>500</td>
<td>12</td>
</tr>
<tr>
<td>10 August 2007, 07:46</td>
<td>44° 35' 04'' N, 37° 52' 48'' E</td>
<td>4500</td>
<td>200</td>
<td>1166</td>
<td>265</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 5. SST charts derived from NOAA AVHRR data. Asterisks mark location of internal wave packets. Positions of ASAR images are marked by the rectangles. Insets show fragments of the ASAR images revealing surface manifestations of IW packets.
IW. Strong near-surface currents modulate the surface wave spectrum resulting in IW manifestation in ASAR images of sea surface. Thus, the IW manifestations on the sea surface are a result of the simultaneous combination of two effects - shallow sharp pycnocline and moving and/or oscillating non-stationary front.

7. Conclusions

In the course of a satellite monitoring campaign of coastal waters of the Black Sea in 2006–2007, surface manifestation of IW packets were registered in SAR images of the sea surface. Joint analysis of SAR, visual and IR data obtained by different sensors at close times indicate that all registered surface manifestations of IW are localized near an eddy boundary or a hydrological front, which suggests a frontal mechanism of IW generation. The results obtained have demonstrated that for a non-tidal sea, a combination of the two conditions - shallow sharp pycnocline and presence of
a moving or inertially oscillating front - may be favourable for IW generation and manifestation in SAR images.

The use of multi-sensor data allowed us to observe and study a complete lifecycle of near-shore vortical structures. A seasonal variability of their manifestations is established.

Operational satellite monitoring provided us with further evidence of a complex near-surface circulation in the test area. We expect long-term regular regional satellite monitoring to provide methods for determining and analysing the generation, persistence and recurrence in space and time of small-scale eddies.

Acknowledgements
This work was supported by Black Sea Scientific Network (Contract no. 022868) and RFBR grants 08-05-00 831-a and 10-05-00428-a. SAR data were obtained under ESA projects C1P.1027 and AO Bear 2775. Aqua/Terra MODIS and NOAA AVHRR data were processed and kindly provided by Dr D. M. Soloviev from the Marine Hydrophysical Institute, Sevastopol, Ukraine.

References


