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OCEANOLOGY

Study of Internal Wave Generation and Propagation Features in Non-Tidal Seas Based on Satellite Synthetic Aperture Radar Data

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Abstract—Despite the intense attention paid to internal wave (IW) investigation, the most experimentally studied and theoretically described are internal gravitational waves in shelf zones of oceans and tidal seas appearing during the interaction of tidal currents with the margin of the shelf. Information on surface manifestations of internal waves in enclosed seas, such as the Black and Caspian seas, is almost absent. In this paper, the results of study of the peculiarities of generation and propagation of nontidal internal waves are presented; the study is carried out on the basis of combined analysis in data of marine surface radiolocation and data of optical and infrared satellite-borne sensors. The experimental basis of investigation is radar images of the marine surface derived with the help of Synthetic Aperture Radars, onboard the Envisat and ERS-2 satellites. Additionally, the data of the following sensors belonging to the optical and infrared ranges were used for the purpose of radar image interpretation: MODIS (onboard the Aqua/Terra satellite), MERIS (Envisat), and AVHRR (NOAA). Surface manifestations of IWs in the northeastern part of the Black Sea and in the Caspian Sea have been found in radar imagery for the first time, their pattern of spatial and temporal variation has been reconstructed. The possible factors leading to generation of the observed nontidal IWs are determined and suppositions about the corresponding generation mechanisms are made. In particular, the IW manifestations recorded in the northeastern part of the Black Sea are localized in the vicinity of the boundaries of eddies or hydrological fronts; this fact evidences for the frontal mechanism of generation, at which IWs are radiated by a nonstationary (moving and/or inertially oscillating) front. The most probable main sources of generation of IWs detected in the Caspian Sea are longitudinal one-knot seiches, whose knot point is located near the Apsheron sill.

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The existence of inner waves (IWs) in the depth of marine waters is caused by stable stratification, which corresponds to water density increase in the direction of gravity force. Inner waves play an important role in processes of horizontal and vertical exchange and mixing of waters, and in the formation of thermohaline circulation of water objects, as well. Motions caused by IWs have a great influence on dynamic processes in the World Ocean and on its surface. The amplitude of IWs can reach one hundred meters in the ocean and the length of waves can reach many kilometers, but variations of the water surface are usually insignificant, at that. Nevertheless, IWs can manifest on the ocean surface under certain conditions, modulating wind ripple by their orbital currents.

Surface manifestations of internal waves (SMIWs) in the ocean are visualized in radar images of the marine surface as alternating bands of enhanced and reduced radar signal; these bands are caused by modulation of the small-scale component of the surface wave spectrum by variable currents created by IWs in the near-surface layer [1–3]. When the data of satellite radiolocation are contributed to IW investigation, the possibilities of deriving information on the sources and mechanisms of generation and on the propagation and interaction of such waves are significantly widened. That is because the data of satellite radar sounding of the marine surface provide a regular survey of water areas with a high spatial resolution (25–75 m) not depending on lighting conditions and cloudiness.

Despite the concentrated attention paid to IW investigation, the most experimentally studied and theoretically described are internal gravitational waves in the shelf zones of oceans and tidal seas appearing during interaction of tidal currents with the margin of the shelf [4]. Experimental investigations are usually carried out in limited water areas and bound to places of stable generation of tidal internal waves. In addition to that, the diversity of conditions in the real ocean, the influence of a great number of factors (of both atmospheric and oceanic origin), and the great complication and costs of *in-situ* measurement cause a certain fragmental picture of processes, which lead to

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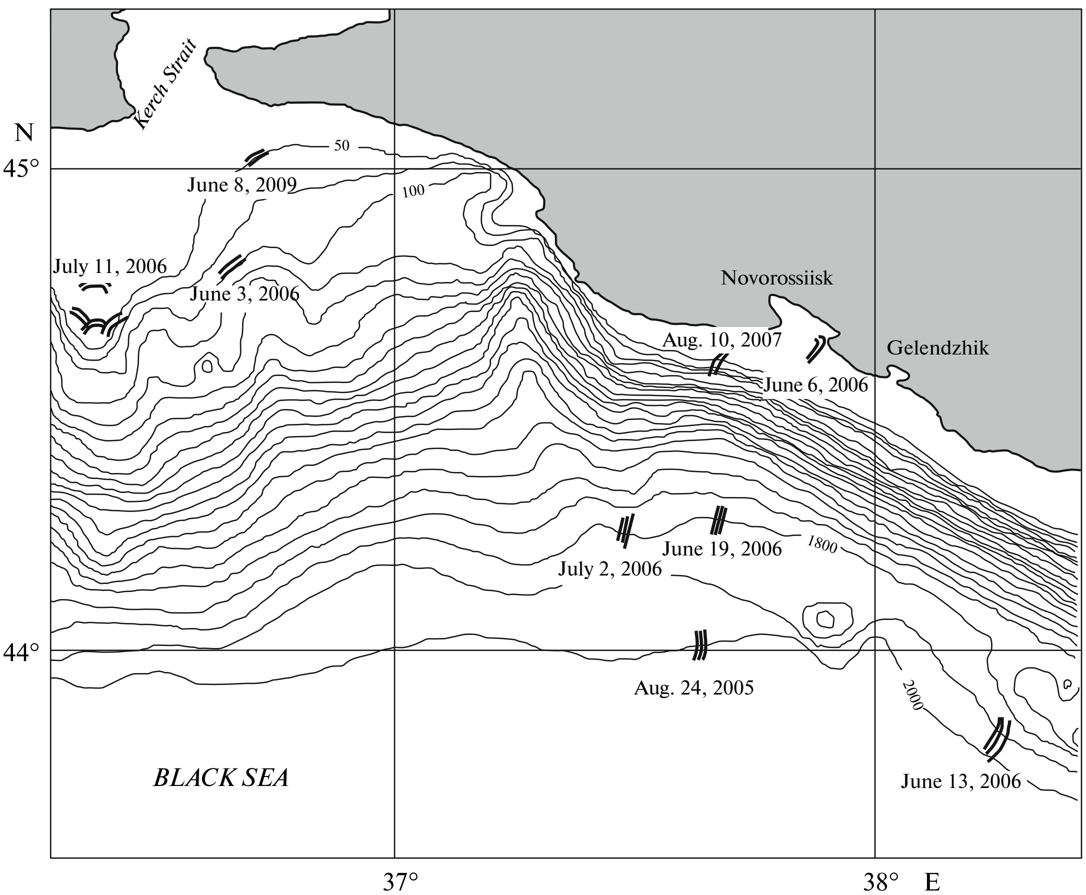

Fig. 1. Schematic map for distribution of SMIWs detected by the results of satellite radiolocation in the northeastern sector of the Black Sea.

generation of internal gravity waves. Information on SMIWs in enclosed seas, such as the Black and Caspian seas, is almost absent. The characteristic feature, which is common for these seas, is that they can be referred to the class of non-tidal seas, because tide-induced water level variations in them are less than ten centimeters. Consequently, in this case, the mentioned mechanism of IW generation by tidal currents is excluded.

Beginning from the 1970s, in shelf zones of the Caspian and Black seas, long-term and detailed investigations of internal waves were carried out for many years. With the help of contact methods, the characteristics of internal waves were measured and the suppositions were made on what dynamic processes in these water areas are responsible for generation of the traits of intensive internal waves [5–8].

Origination of internal waves in these seas is possible during implementation of active dynamic processes related to the appearance and relaxation of near-coastal upwelling, onset-offset phenomena, inertial oscillations, varied-scale eddies, oscillations of hydrologic fronts, etc. Regular satellite monitoring of the marine surface, which is being implemented by the Space Radar Laboratory, Space Research Institute, Russian Academy of Sciences, since 2005 in the northeast of the Black Sea and since 2009 in the Caspian Sea, has allowed us, first, to detect surface manifestations of internal waves in radar and optical images of tideless seas, and, second, to reconstruct the pattern of their spatial and temporal variability. Additionally, complex use of data, which differ in their physical nature (active and passive microwave sounding, optical and infrared data), spatial resolution, and bandwidth of survey, has given the unique possibility to reconstruct an entire view of meteorological and hydrodynamic phenomena and processes in the chosen areas. On the basis of parameters derived from remotely sensed data, the possible factors leading to generation of visible internal waves of nontidal genesis are determined and the suppositions on the corresponding generation mechanisms are made.

The experimental basis of the investigation is radar images of the marine surface derived with the help of radars with a synthesized aperture onboard the Envisat and ERS-2 satellites. Additionally, for the purpose of radar image interpretation, the data of the following sensors belonging to the optical and infrared ranges

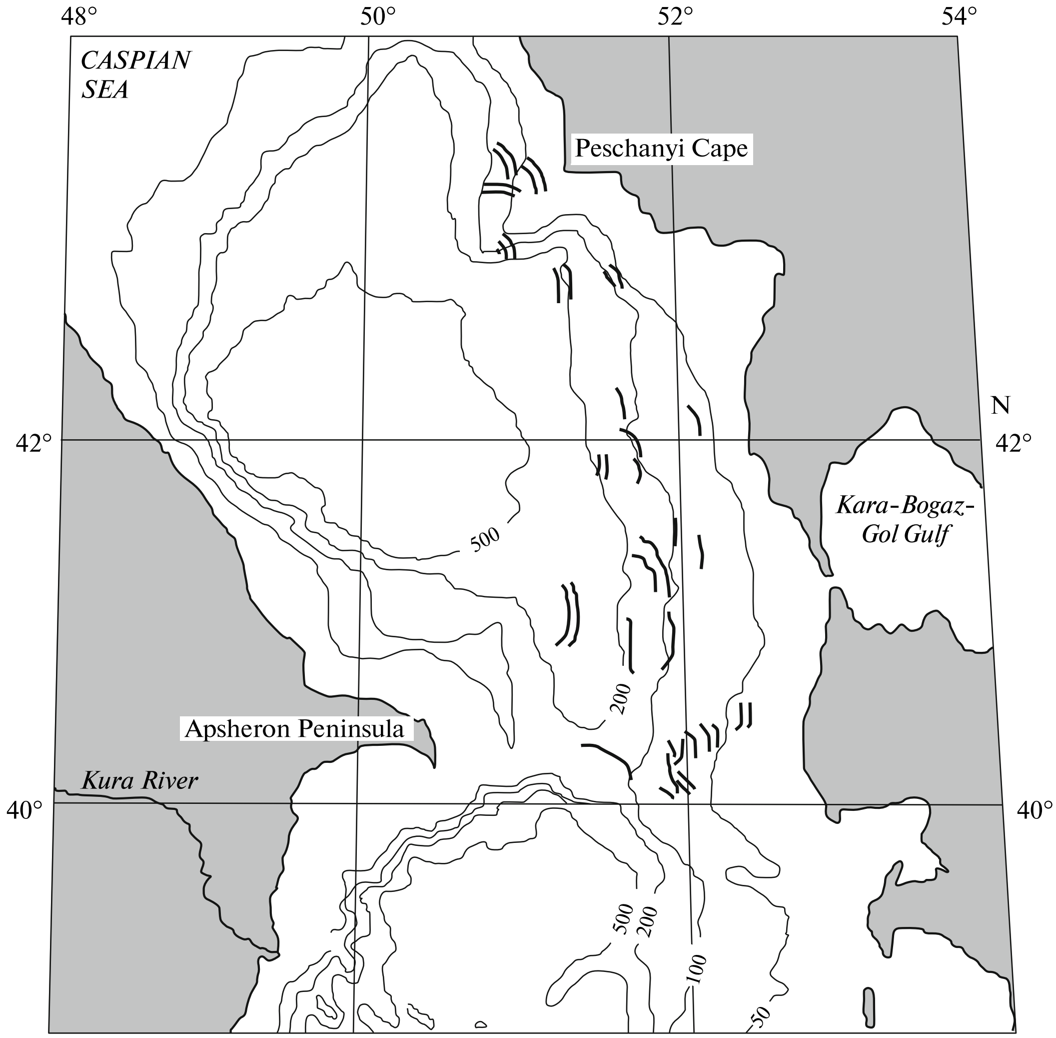

Fig. 2. Schematic map for distribution of SMIWs detected by the results of satellite radiolocation in the central part of the Caspian Sea.

were used: MODIS (onboard of Aqua/Terra satellite), MERIS (Envisat), and AVHRR (NOAA); these data carry the information on temperature fields of the marine surface and on mesoscale dynamics of waters. In the Caspian Sea monitoring, data of scanning radiometer ETM+ onboard the Landsat-7 satellite were additionally used. On the whole, more than 1000 satellite images of the marine surface in the study areas were obtained and processed during the observation period. The great volume of experimental material provided the statistical reliability of the study results.

On the basis of targeted marine surface radar imagery processing, phenomenological identification of radar patterns for SMIW, varied-scale eddy structures, frontal zones, and upwelling zones was implemented. The maps of spatial distribution for nontidal SMIWs detected by radar data in the northeastern part of the Black Sea (Fig. 1) and in the central part of the Caspian Sea (Fig. 2) during the observation period are plotted, and areas of nontidal IW origination and propagation are localized.

As is seen from Fig. 1, three areas of SMIW concentration can be distinguished in the northeastern part of the Black Sea: the Kerch pre-strait area above isobaths of 50–100 m; the area near the Tsemes Bay above isobaths of 40–50 m; the area located 25–28 miles southwestwards from the Novorossiisk–Tuapse coastline above isobaths of 1800–2000 m. Most of the observations are made in periods from the beginning of June until mid-July.

During the monitoring of the Caspian Sea water area in 2009, numerous surface manifestations of IW trains have been recorded in the period since the end of May until the end of August. The three principal areas of their localization are determined depending on the season: the southwestern part of the Caspian Sea, near Cape Limir (end of May); the eastern part of

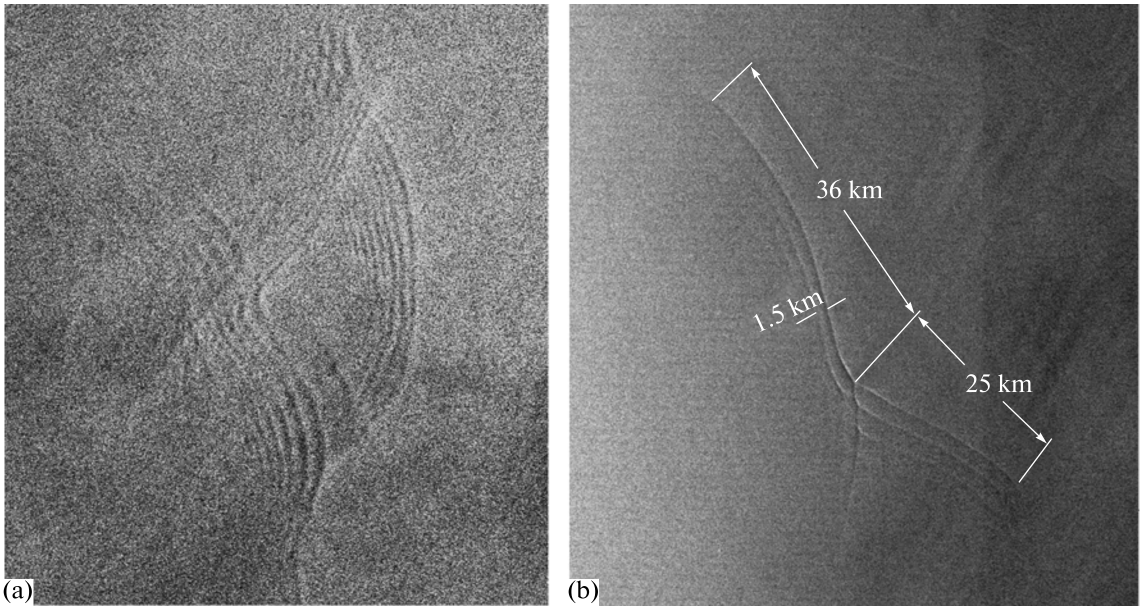

Fig. 3. Examples of surface manifestations of internal wave trains nonlinear interactions in the Caspian Sea: (a) fragment of the ASAR Envisat (15 × 16 km) taken at 06:47 UTC on August 22, 2003, with 12.5 m resolution; (b) fragment of the ASAR Envisat image (65 × 65 km) taken at 18:23 UTC on July 24, 2009, with 75 m resolution.

the sea from Bekdash Cape to Chekelen Peninsula (June–July); the eastern part of the sea from Aktau to Kazakh Bay (August). Similar results are obtained from analysis of archive data on 2003 and 2007.

In order to explain the seasonal variability of SMIW, a comparison is made between the results derived from satellite data and in-situ measurements. The maximal SMIW appearance corresponds to the presence of a sharp and shallow pycnocline. Such conditions are favorable for both origination of internal solitons and manifestation of these solitons on the marine surface, because such conditions provide development of strong orbital currents in the near-surface layer that leads to modulation of the surface wave spectrum and to manifestation of internal waves in radar images of the marine surface. The main spatiotemporal characteristics of nontidal IWs (detected from remotely sensed data) are determined by satellite data, namely, the wavelength, number of wave trains and number of waves in a train, propagating direction, refraction, and the length of the leading wave front and its orientation.

The fact of SMIWs registration in radar imagery of the northeastern part of the Black Sea is a relatively rare event. Only nine cases of SMIW detection in radar images of the marine surface for this water area are recorded for the period of 2005–2009. In the northeastern part of the Black Sea, IWs are manifested as isolated wave trains containing up to 20 waves, and the maximal wavelength in a train does not exceed 500 m, at that. The front of a leading wave is usually curved, and its length is varied from 7 to 18 km. The width of trains is varied from 0.85 to 3.5 km depending on the number waves in a train. Detection of SMIWs with relatively small spatial scales in the northeastern part of the Black Sea has become possible because of using satellite radar data with a high spatial resolution.

Surface manifestations of internal waves in the Caspian Sea are more numerous (27 radar images containing SMIWs are recorded in 2009 alone), and they significantly differ from waves of the Black Sea in their phenomenological features. In one image of size is 400 × 400 km, several IW trains are usually detected and the number of trains reaches six. This evidences for the presence of several places of wave generation spaced a relatively small distance from each other. SMIWs in the Caspian Sea have the form of classical solitons. The curves of fronts, phase shifts, and other effects typical for nonlinear interactions are observed for interacting trains. In most cases, trains propagate shorewards and are observed above depths of 50–200 m. The front length of a leading wave in a train can reach 1500 m, and prolongation of fronts is up to 50 km (Fig. 3).

It is found that all the SMIWs recorded in the northeastern part of the Black Sea are localized in the vicinity of the boundary of eddies or hydrological fronts; this fact evidences for a frontal mechanism of generation, at which IWs are radiated by a nonstationary (moving and/or inertially oscillating) front [9]. In particular, the radar image in Fig. 4b exhibits a moving and evolving eddy dipole. The mushroomlike structure, which coincide with the dipole by form and location, is clearly seen in the sea surface temperature

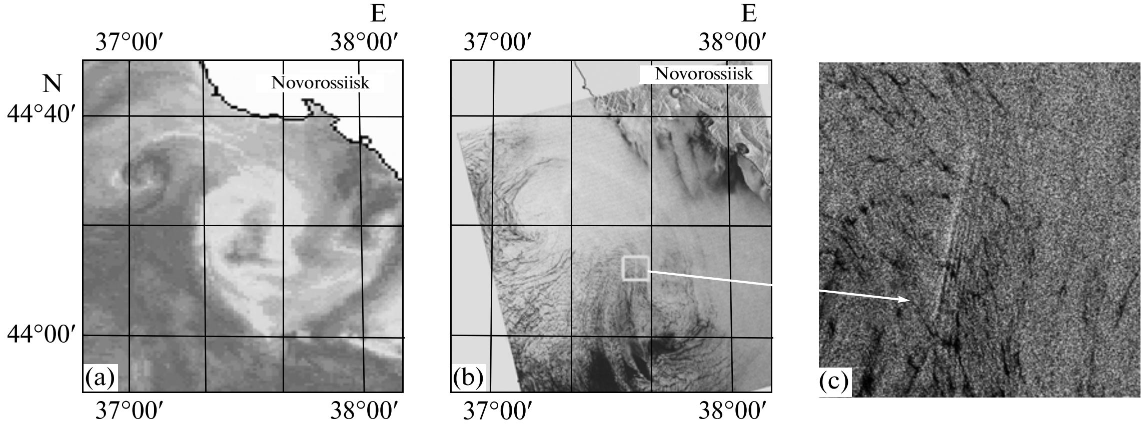

Fig. 4. Sea surface temperature charts derived from NOAA AVHRR data, June 19, 2006, 23:57 UTC (a); ASAR Envisat image taken at 19:10 UTC on June 19, 2006 (b); radar imagery of IW train (c).

field, reconstructed on the basis of infrared satellite data (Fig. 4a). In the radar image, the surface manifestations of the internal wave train are found; manifestations are localized in the vicinity of the boundary for the anticyclon component of the eddy dipole. The most probable main sources of generation of IWs detected in the Caspian Sea are longitudinal one-knot seiches, whose knot points were located near the Apsheron Sill, as well as upwelling, which is often manifested in the vicinity of the east coast.

The obtained results prove that satellite radar remote sensing of the marine surface is an effective tool for observation and study of internal waves in closed non-tidal seas, which are significantly distinct in their physical–geographical features, by the structure of the main currents, by the features of the hydrological regime and the formation of the seasonal thermocline, by the directions of predominant winds, and by the state of the near-surface layer of the atmosphere. One can claim that IWs in non-tidal seas are less intensive than IWs induced by tidal currents in the oceanic shelf, but IWs of non-tidal seas are distinct for a variety of generation sources. Further regular satellite monitoring of the chosen study areas and generalization of the obtained results will enable us to estimate the relative contribution of various generation mechanisms of nontidal nature internal waves into intensification of the internal wave field.

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