Description of the vertical density structure obtained from internal wave observations at the Black Sea shelf

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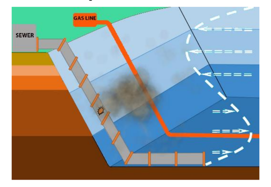
Motivations

Internal waves are waves that travel within the interior of a fluid, they exist in the stratified fluids [1]. The action of internal waves may influence the security of man-made constructions at the sea shelf. The transport of pollution in the sea is associated with cross-isopycnal mixing caused by breaking of the internal waves.
Comparison between the latest satellite data and multi-year measurements offer an opportunity to assess parameters of these waves.



Goals

(1) Assess the internal waves parameters produced by satellite observations using comparisons with numerical experiments at the shelf of the Black Sea, near the Heracles Peninsula.
(2) Examine available satellite datasets to determine the conditions when internal waves appear at the coast.
(3) Establish theoretical spatio-temporal characteristics of internal waves that correspond to shallow pycnocline.

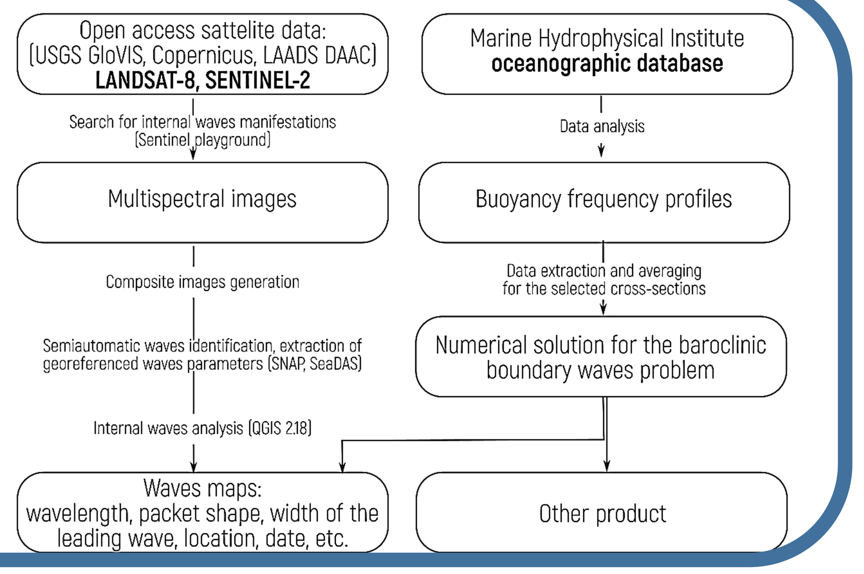
Methodology

The research plan contains 3 defined steps as follows:

Step 1. Detection of the appearance of internal waves from open databases
https://scihub.copernicus.eu/dhus/#/home
http://glovis.usgs.gov/
https://earthexplorer.usgs.gov/

Step 2. Numerical analysis

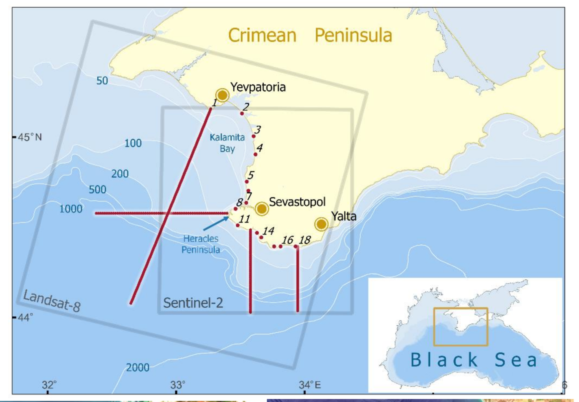
Step 3. Formation of a database of internal waves of the Heracles Peninsula



Study area and datasets

Areas of the Crimean coast shelf determine the conditions for the generation of internal waves

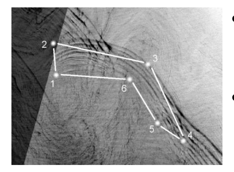
- The areas between Yalta and the extreme southwestern tip of the Crimean Mountains, the width of the shelf is 30–40 km.
- The areas to the North of the Heracles Peninsula – in Kalamita Bay, between the cities of Sevastopol and Yevpatoria, the width of the shelf is 100–150 km.



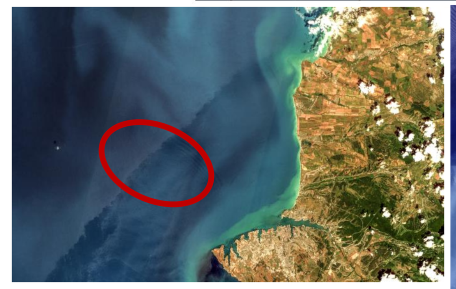
Satellite data

High resolution images from *Landsat*-8, *Sentinel*-2 satellites for 2017 are analyzed. Reading and processing of satellite images was performed in the *SNAP Desktop* environment.

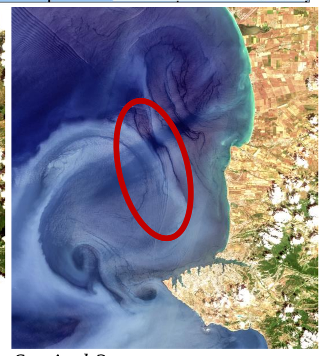
For each packet of internal waves, the direction of propagation is noted, as well as 6 points describing its shape.



- Perimeters with geographic reference of 6 points for each wave (3 front and 3 rear) were obtained.
- The parameters of the waves (front width, wavelength, number of waves in the packet, direction, date) are included in database.



Landsat-8
NASA



Sentinel-2
EU Copernicus Programme

Measurement data

Decadal temperature and salinity fields at standard levels in the 0-1500 m layer in the Black Sea were reconstructed using in-situ data and satellite measurements which had been collected from the 1950 up to nowadays [2].

(1) Measurements on temperature and salinity from 1951-2008 from the Bank of Oceanographic Data of MHI RAS.
(2) Temperature and salinity measured by deep sea buoy–profilers (565 profiles for 2005-2008).
(3) Monthly averages of nighttime satellite measurements of SST at a 4×4 km grid for 1985-2007.

Theoretical model for internal waves

The linearized equations of motion under the Boussinesq approximation are as follows:

$$\rho(u'_t - fv) = -P'_x,\ \rho(v'_t + fu) = -P'_y,\ \rho w'_t + \rho' g = -P'_z,\quad u'_x + v'_y + w'_z = 0, \quad (1)$$

$\rho(z)$ – background density; ρ' – density perturbation; P – pressure; u, v, w – velocity components; y – offshore coordinate; $f = 1{,}01\cdot10^{-4}$ s^{-1} – Coriolis parameter. The system (1) can be reduced to one equation for the vertical velocity component $w = W(z)\exp[i(kx + \omega t)]$, k – wavenumber along the horizontal plane, ω – wave frequency:

$$W''_{zz} + k^2[(N^2 - f^2)/(\omega^2 - f^2) - 1] = 0,\ W(0) = W(H) = 0, \quad (2)$$

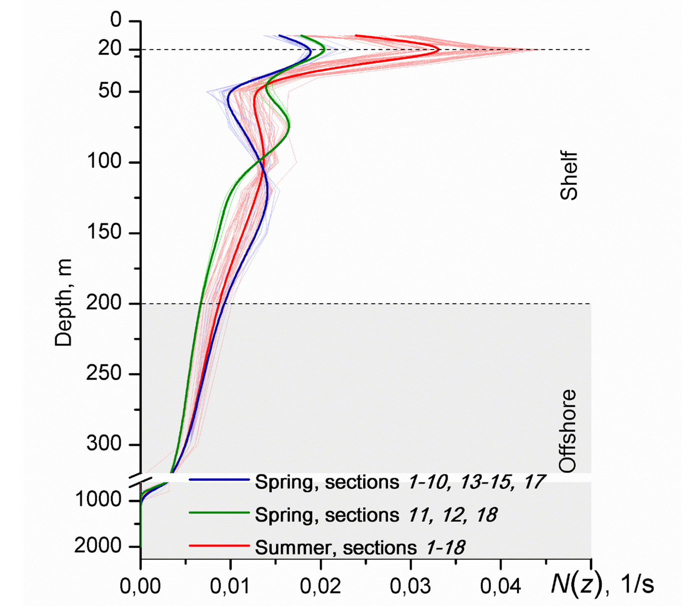
$N(z)$ – buoyancy frequency. Approximating the derivatives with the finite differences discretized over Δz yields an eigenvalue problem [3]:

$$\mathbf{AX} = k^2\mathbf{X}\,. \quad (3)$$

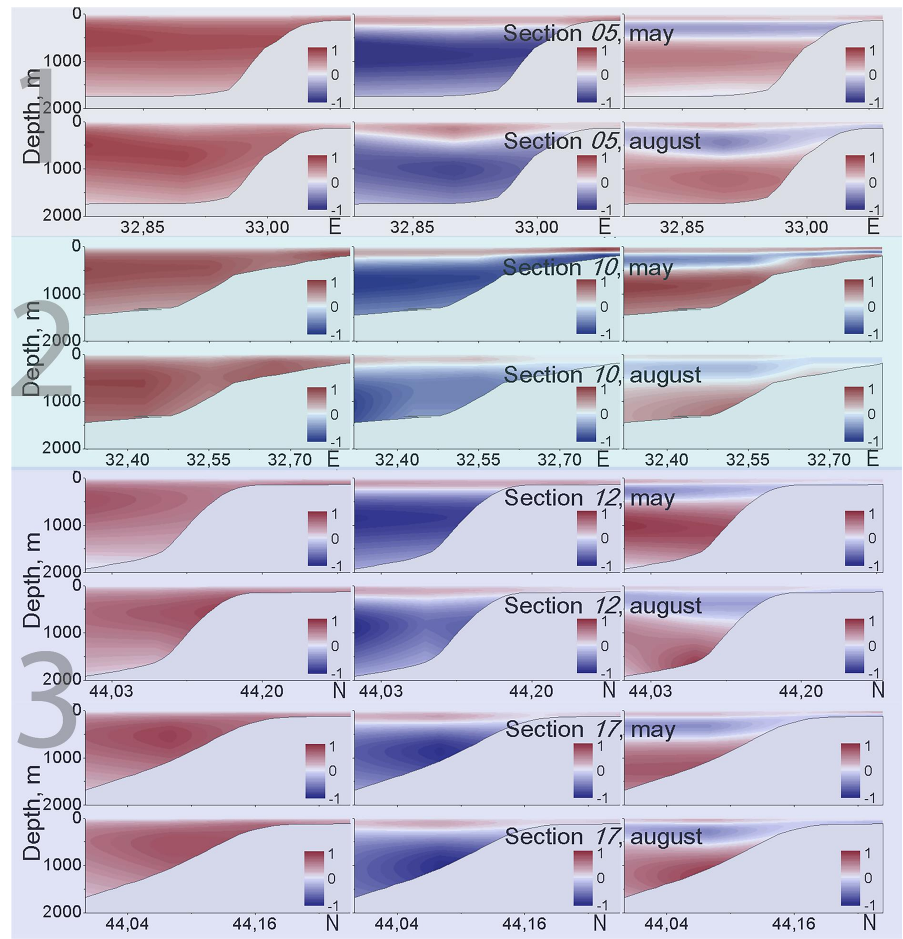
The internal waves dispersion characteristics and the normal mode vertical velocity component profiles were estimated numerically (3).

Results

(1) Analysis of buoyancy frequency profiles

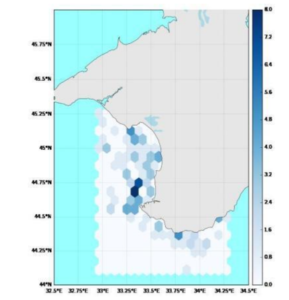


In spring:
seasonal pycnocline 0.0018-0.024 s^{-1} (depth 20 m),
main pycnocline 0.014-0.015 s^{-1} (depth 89 m).
In summer:
seasonal pycnocline 0.01-0.04 s^{-1} (depth 20 m),
main pycnocline 0.028-0.032 s^{-1} (depth of 115 m).

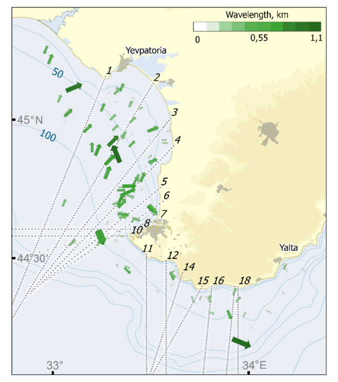


The vertical velocity profiles for the three modes were received by solving numerically the boundary value problem. Results of numerical experiment for a summer profile of $N(z)$.

(3) Analysis observations



Two-dimensional histogram of the occurrence of internal waves



Internal wave appearance scheme

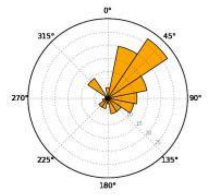
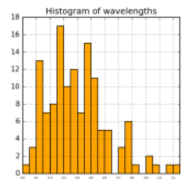


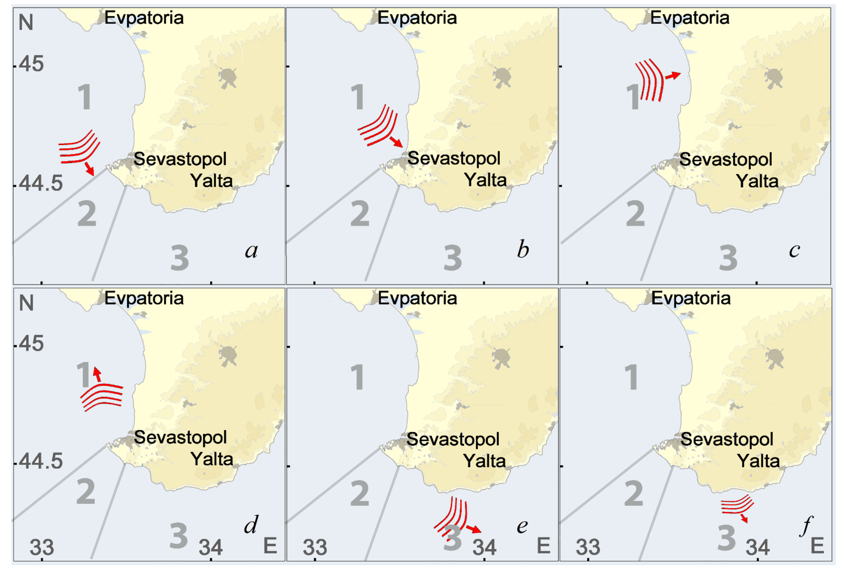
Chart of recurrence of the directions of internal waves



Histogram of the frequency of internal wavelengths

(2) Comparisons of model calculations with satellite observations

Profile	Simulation Results		Satellite Data			
	Mode	Wavelength, m	Data	Satellite	Direction	Wavelength, m
1	1	2416	25.06.2017	Landsat-8	NNW	1064
	2	950	30.05.2017	Sentinel-2	NE	817
4	1	770	26.06.2017	Sentinel-2	ENE	707
	2	290	26.06.2017	Sentinel-2	E	780
5	1	1197	28.08.2017	Sentinel-2	SSE	901
	2	596	11.07.2017	Sentinel-1	E	528
10	1	996	28.08.2017	Landsat-8	SSE	731
	2	599	28.08.2017	Sentinel-2	SSE	791



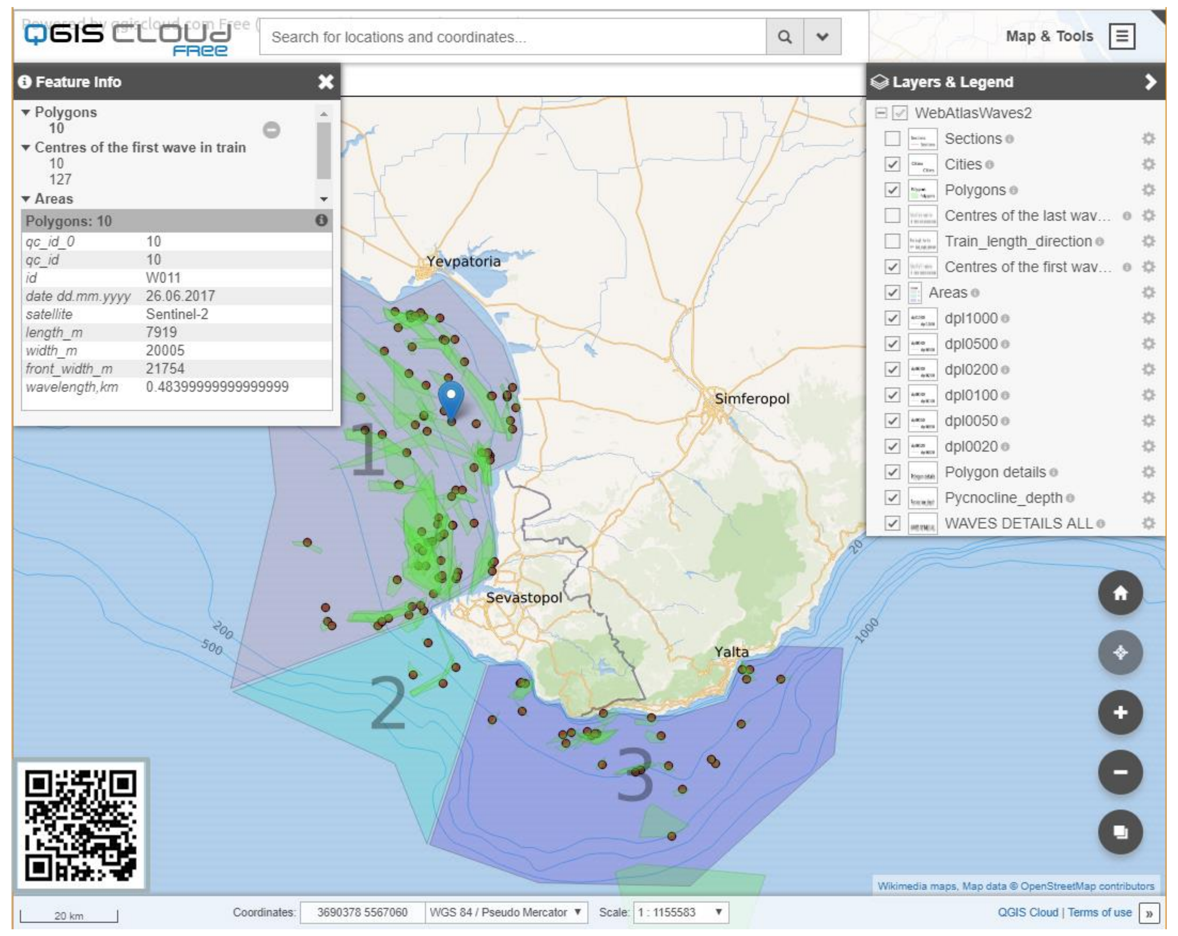
Schematic maps showing the direction of propagation of internal waves relative to the coastline or shelf edge

Usability and accessibility

As a result of this study a database was made including the simulation and observations data of internal waves in the area of the Heraclea Peninsula.

Database include information about location, direction, wavelength and phase speed of internal waves.

1. ***Merged sections*** – the position of the cuts 1–18, the depth of the seasonal and the main pycnocline, the calculated standard quadratic deviation for the period from May to August.
2. ***Polygons details*** – areas of internal waves, with details of the date, satellite name, wavelength and geometric parameters of the package.
3. ***Centres of the last wave in train*** – position of the last wave in the packet, date, wavelength, type of satellite, depth of the location of detection.
4. ***Centres of the first wave in train*** – position of the first wave in the packet, date, wavelength, type of satellite, depth of the location of detection.
5. ***Train length*** – wave vector showing the direction of propagation of the packet and its length.
6. ***Areas DATA*** – three areas in the study area, differing by the type of shelf and the frequency of observation of internal waves. It contains information on the average median value of the wavelength, its minimum and maximum values, and also on the total number of waves during the study period.
7. ***Model Data*** – information on the theoretical parameters of the highest modes of internal waves: length, period, phase velocity.



Vertical density structure

Based on the collected data we can obtain the phase velocity of the waves and calculate the depth of the Väisäl – Brunt frequency maximum, if the mode structure of the waves and the characteristic density difference in the selected region are known.
The dispersion relation for the lowest internal mode [4]:

$$c^2 = (g/k)(\Delta\rho/\rho)(\mathrm{cth}kh + \mathrm{cth}k(H-h))^{-1}$$

h - pycnocline depth; H - sea depth; c - phase speed; $\Delta\rho$ - the difference in density of water below and above the pycnocline.

Highlights and conclusions

This study represents an analysis of the main parameters of internal waves at the shelf of the Heracles Peninsula according to observations and numerical analysis.

(1) The direction of wave trains propagation is mostly North-Eastern.
(2) Mean wavelength is around 0.4 km.
(3) Phase velocity of internal waves at the shelf of the Black Sea for the first mode varies from 0.02 to 0.81 m/s; for the second mode – 0.01–0.41 m/s; for the third mode – 0.001–0.26 m/s.
(4) Database that contains the simulation and observations results is designed as an online resource https://qgiscloud.com/April/WebAtlasWaves2.

Work in progress

(1) Identification of the phase velocity of internal waves from sequential satellite images.
(2) Calculation of the maximum depth of buoyancy frequency based on two-layer approximations for long and short internal waves.

References

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[4] Phillips, O.M. (1997), The dynamics of the upper ocean. New York: Cambridge Univ. Press. 366 p.

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