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Tetiana A.Melnichenko

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Оцінка активності виходів метану з дна Чорного моря за матеріалами зйомки супутника MODIS та геолого-геофізичними даними.

Мельниченко Т.А.

ДУ «Науковий центр аерокосмічних досліджень Землі Інституту геологічних наук НАН України», Київ, Україна. E-mail: meltanua777@gmail.com

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Анотація. Наведено результати певного етапу дослідження. Виявлено особливості характеристик виходів газу метану в перехідній зоні шельф-континентальний схил на ділянці палеodelти Дніпра в північно-західній частині Чорного моря з урахуванням комплексу даних: інформації космознімків супутників та геолого-геофізичних (акустичних) даних. Проведено моніторинг близько 2000

знімків супутника Modis/Terra (продукт MOD021KM). Знімки оброблено в ГІС-середовищі. Установлено, що об'єм газу струменевих виходів метану на досліджуваній ділянці фіксується на космознімках супутника Modis та найбільше проявляється під час підвищеної сейсмотектонічної активності (активізації землетрусів у Чорноморському регіоні) – це пов'язано з тектонічною структурою ділянки вивчення, яка розташована в регіональному плані на краю Східно-Європейської платформи, а в локальному – є палеodelтою Дніпра в зоні розшліщення, являє собою додатковий фактор для виходів газу саме тут. На космознімках фіксується незначна хмарність у безхмарну погоду або відсутність хмар на тлі суцільної хмарності. Це пояснюється фізичними властивостями метану, який становить (за даними геохімічних досліджень) близько 99 % складу газу, що виділяється. Метан, піднімаючись із дна моря до поверхні, а далі до тропосфери, значно холодніший за поверхневі води та тепліший, ніж шари атмосфери, що провокує утворення конденсату над ділянкою з виходами метану, а коли погодні умови змінюються, утворюючи дощову хмарність із різким пониженням температури, метановий газ стає значно теплішим і, піднімаючись угору, розпорошує хмари, утворюючи ділянку безхмарності на тлі суцільної хмар.

Ключові слова: струменеві виходи газу (метану), Чорне море, знімки із супутника Modis

Estimation of activity the methane seepage from the Black Sea floor using MODIS images and geosciences data

Melnichenko T.A.

State institution "Scientific centre for aerospace research of the Earth Institute of geological science National academy of sciences of Ukraine", Kyiv, Ukraine, E-mail: meltanua777@gmail.com

Abstract. The publication presents the results of a certain stage of the study: the features of methane gas seepage characteristics in the transition zone of shelf-continental slope in the region of the Dnieper Paleodelts in the northwestern part of the Black Sea are identified, taking into account the data set: information of satellite images and of geological-geophysical (acoustic) data. About 2000 of the MODIS satellite images (product MOD021KM) are acquired in stages over one year period. The image processing was carried out in the GIS environment. It was established that the volume of methane gas seepage on the investigated site is fixed on satellite images and is most pronounced during increased seismotectonic activity (activation of earthquakes in the Black Sea region) - this is due to the tectonic structure of the study area, which is in the regional plan on the edge of the Eastern European platform, and in the local area, is the Dnepr paleo-delta in the zone of decomposition, which is an additional factor for gas outlets here. On satellite images small clouds are observed in cloudy weather or absence of clouds on the background of continuous clouds. This is due to the physical properties of methane, which is (according to geochemical studies) about 99% of the released gas. Methane rising from the bottom of the sea to the surface, and then to the troposphere is much colder than the surface water and warmer than the atmosphere layer, which provokes the formation of condensate over the site with methane gas seepage, and when the weather conditions change, forming a rainy cloud with a sharp drop in temperature, the volume of methane gas of seepage up are much warmer than clouds, forming a cloudy area on a background of continuous clouds. This phenomenon is recorded in various spectral (thermal and infrared) bands in satellite images (NASA – MODIS, NOAA, etc.), methane rising to the lower layers of the atmosphere intensively absorbs thermal radiation of the Earth in the infrared spectral region at a wavelength of 7.66 μm . It enables to determine the methane gas seepage in satellite images for future studies of gas outlets from the bottom of the sea, taking into account the geological information and additional hydrological

and weather data. The conducted monitoring of the satellite images showed that during the period of increased seismic activity in this region (in particular under the influence of the zone Vrance), it directly affects the tectonic situation in the northwestern part of the Black Sea and increases the emissions of methane gases from the bottom of the sea, which are then recorded on the MODIS sensor.

Keywords: gas seepage (methane), tectonics, Black Sea, MODIS satellite images, remote research.

Introduction. Gas seepage in the Black Sea is first mentioned in scientific literature in the XIX – XX centuries by the scientists such as M. I. Andrusov and others. In the 80-s of the past century the scientists, investigators and researchers from the Scientific Institutions and Hydrographical Services of the Black Sea Fleet have discovered the fluidic gas seepage in the Black Sea near the cost of Bulgaria. Since the 1990s and through the 2000-2014 the numerous marine researches, geological, geochemical, hydroacoustic and hydrobiological studies have been carried out by the different scientists among those (Naudts et al., 2006; Popescu et al., 2007; Shnyukov et al., 2014, 2015). The study of relationship between the areal distribution of methane emanation, seafloor morphology and its deep structures is provided by comprehensive multipath seismic and hydroacoustic surveys of water column (Egorov, et al., 2011).

Urgency of the research of methane emanation (gas flames, seeps), which are located at the seafloor is connected with the prospects for its exploitability. This is substantiated by the drilling work for natural gas production from the deposits of methane catharases, which are actually connected with methane leakages on the sea floor, for example, at the Daini-Atsumi Knoll methane hydrate reservoir in the eastern Nankai Trough, Japan (Yamamoto, 2015; Fujii, 2015). In Ukraine according to the Ukrainian Independent Information Agency (www.unian.ua, 2017)

the state-owned public joint stock company Ukr-GasVydobuvannya plans to begin the natural gas production at the continental shelf of the Black Sea and for 5-7 years the gas output can achieve 5 billion cubic meters per year.

The gas emissions in the marine surroundings are distributed throughout almost all shelf zones of oceans and seas and connected with the occurrences of gas hydrates (Fleischer et al., 2001).

In the Black Sea the most gas seepages are concentrated in the transit zone between the shelf and continental slope in the paleodelta of the Dnieper at the north-western self. The exploration survey companies (Shnyukov et al., 2015; Egorov et al., 2011) and geophysical and other alternative methods revealed near 2724 methane seepages at the depths from 66 to 825 (to 700 m by Shnyukov et al., 2014 and others) and the gas flame height of 230 m. On a basis of geochemical analysis (Lejn, Ivanov, 2005) just methane is 95 to 99.5 vol%.

Thus, the object of research is the test site in the north-western area of the Black Sea at the coordinates of $34.5^{\circ} - 36.5^{\circ}$ E and $43.5^{\circ} - 44.5^{\circ}$ N (Fig.1), which was attractive for many foreign and Ukrainian researches, where the numerous marine cruises (Egorov et al., 2011; Naudts et al., 2006; Shnyukov et al., 2014 and others) were conducted.

Fig. 1. Test site on the Black Sea map fragment (acvatoria.org.ua/maps) with the charting methane seepages by Egorov et al., 2011. Symbols: green circles are methane seepages plotted on the map using the coordinated of Egorov et al., 2011; red rectangle is the test site at the coordinates of $34.5^{\circ} - 36.5^{\circ}$ E and $43.5^{\circ} - 44.5^{\circ}$ N.

The goal of research is to detect and describe the general characteristics of the manifestation of gas seepages within the test site of the Black Sea in the paleodelta of the Dnieper region as well as study the features for the methane seepages using a set of methods, i.e. aerospace studies, geological and geophysical data.

Materials and Methods. Research focuses on the MODIS data (MOD21KM product) received in the open access at the official NASA site: <https://ladsweb.modaps.eosdis.nasa.gov/search> using geological and geophysical data on the manifestation of methane emanations (Egorov et al., 2011; Yamamoto, 2015; Lejn, Ivanov, 2005; Tolkachev, 2014; sites.google.com.). MODIS or Moderate Resolution Imaging Spectroradiometer, is an instrument aboard the TERRA satellite including two scanning modules with its sweeping 2,330-km-wide viewing swath. Sensor acquires data in 36 discrete spectral bands (11 visible, 9 infrared, 6 thermal, 4 short-wave infrared, 6 long-wave infrared bands) (uk.wikipedia.org.2008.MODIS).

The studies addressing to the mineral exploration by means of remote sensing methods (Lyalko, Popov, 2017) at the current stage of development of science and technologies are the promising and encouraging due to lower costs than the direct geological methods.

Hence, this study uses satellite data taking into consideration already known geological and geophysical information, etc.

This study is based on the search, selection and processing of satellite images, which can be used to reveal the anomalies over the methane seepage. In order to achieve this aim the monitoring of MODIS images for 2000 – 2003 were conducted. The most attention is given to the seismotectonic activity of the Black Sea region in 2000 (earthquakes in Turkey and Romania). The previous studies (Melnichenko, 2015; Melnichenko, Vorobiev, Geykhman, 2016; Vorobiev, Melnichenko, 2016) have shown that the seismic activity within the north-western shelf of the Black Sea provoked the increases of the volumes of methane emission.

Considering the above information some satellite images with the probable anomalies were selected in the transit zone, i.e. shelf – continental slope with the abrupt change of the depths that can be observed in the relief, geological and tectonic structure of the Black Sea.

Research methodology includes the few steps: firstly, the satellite images are selected and analyzed to detect the anomalies at the sea surface within the test sites aiming to determine the period of the methane seep from the seafloor to the sea surface; secondly, application of GIS-programs to the pro-

cessing of satellite images; finally, the additional description of spatial position for gas seeps and the performing the statistic analysis (percentage of the amount of seeping methane relative to the depth, where this seepage was identified).

Selected MODIS images with the features in the various spectral ranges were analyzed in the following bands:

2nd NIR band, 841-876 nm, spatial resolution is 250 m; thematic direction is land boundaries and cloudiness boundaries;

5th SWIR band; 1230-1250 nm, spatial resolution is 500 m; thematic direction is the properties of the terrestrial objects and cloudiness;

6th SWIR band, 1628-1652, spatial resolution is 500 m; thematic direction is the properties of the terrestrial objects and cloudiness;

7th SWIR band, 2105 – 2155 nm, spatial resolution is 500 m; thematic direction is the properties of terrestrial objects and cloudiness;

8th visible band, 405 – 420 nm, spatial resolution is 1000 m; thematic direction is the hydrological properties, phytoplankton, biogeochemistry;

13th visible band, 662-672 nm, spatial resolution is 1000 m; thematic direction is the hydrological properties, phytoplankton, biogeochemistry;

19th NIR band, 915-995 nm, spatial resolution is 1000 m; thematic direction is the atmospheric water vapor.

Results and their analysis. As a rule, methane seepage is associated with the abrupt bend of the seafloor slopes and connected with the zones of higher fracturing and tectonic faults. Now there are more 40000 methane seeps and generally they are located at the depth of 50 m to 700 m. Their heights are less than 200 m. Most of them don't reach the sea surface, but some cases of the direct methane output at the sea surface are known (Shnyukov et al., 2015).

According to the geological and geophysical data acquired by the many cruises over the test site near 2 thousands methane seeps of the seafloor are identified. The concentration of such amount of point output of fluid methane within the local area emits the considerable gas volume, which rising from seafloor to the sea surface forms the anomaly zones of accumulation of some cloudiness or its lack at the background of general cloudiness. This phenomenon is detected on the MODIS, NOAA and other images in the different spectral (thermal, IR) ranges and connected with the properties of methane (Bashin, 2010), which rising upwards to the lower atmosphere absorbs heat radiation of the Earth in the IR range at the wavelength of 7.66 μm .

In the troposphere the temperature behavior changes with the height reducing on average by 6°C per each kilometer or 11 mmHg per each 100 m (uk.wikipedia.org). The conventional boundary of

the troposphere is tropopause, where the reduction of temperature with the altitude ceases. Methane with hydrogen sulfide and other gases passes through the tectonic faulting zones and fissured rock in the seafloor generating gas blowouts (Shnyukov et al., 2015).

Methane passing through the water column from the seafloor to sea surface carries out water masses at the lower temperatures, which are detected on the satellite images during the summer period, when the difference between sea surface temperature ($\sim 25^{\circ}\text{C}$) and near-bottom water ($\sim 3\text{-}5^{\circ}\text{C}$) is noticeable (Vorobiev, Melnichenko, 2016).

Methane volume transporting from the seafloor to surface is crucial, however, at the present stage the value of this volume can't be determined. Thus it is known that gas volume is increasing during the increase in tectonic and seismic activity in the region.

After the analysis of the series of MODIS images (MOD021KM product) over the test site the accumulations of some cloudiness were identified and they are marked by red rectangular in Figure 2 with

the centre of $45^{\circ} 28' \text{ N}$ and $32^{\circ} 11' \text{ E}$ that was interpreted as a methane seepage in the form of condensed fluid.

The temperature difference plays the crucial role in this process, since methane rising from the seafloor to the surface and further to the troposphere is cooler than the sea surface water and warmer than the atmospheric layers, this provokes the condensate formation as some cloudiness over the methane seepage area. On a cloudless day these events are detected on the satellite images. Conversely, when the weather conditions change forming the rain cloudiness with the abrupt temperature decreasing relative to surrounding conditions, the volume of much warmer methane scatters the clouds and provokes the appearance of the area without the cloudiness at the background of cloud cover. This phenomenon is clearly observed at the satellite images (Fig. 3) in all spectral bands, the most explicitly and remarkably in 5, 6 and 19 bands. The anomaly is detected among the clouds (as a result of heat flux caused by the gas seepage) and it is observed at the satellite images without clouds. The next stage of the study is the processing satellite images by means of GIS-program with the attention to the test site.

Fig.2. MODIS scene fragment (MOD021KM product) with the isolated anomaly zone in the study region; date and time of survey are 13.07.2000 and 8:55; SWIR region ($1.230\text{-}1.250 \mu\text{m}$) (500 m spatial resolution), cloud cover zone is clearly observed and interpreted as an anomaly located over the study region and methane seepage.

Fig. 3. MODIS scene fragment (MOD021KM product) with the isolated anomaly zone in the study region; date and time of survey are 3.03.2000 and 9:20; SWIR region (1.230-1.250 μm) (250 m spatial resolution), a zone without cloudiness is clearly observed at the background of cloud cover; this zone is interpreted as an anomaly located over the study region and methane seepage.

The study area is located within the regional zone of tectonic fault and the edge of the East European Craton, where the methane is discharged. The accumulations of this methane are connected with the formation of gas hydrates, which serve as the natural reservoirs.

Just at the area of the Dnieper River canyon in the Black Sea there is the fault zone edge (plunging) of AR-PR basement that is expressed in the sea floor relief as a transition zone of the shelf – continental slope, where heat flux is periodically emanated and even more powerfully during the higher tectonic activity seen on satellite images in the shape of anomaly spots without cloudiness (Vorobiev, Melnichenko, 2016) at the background of the cloud cover (Fig.3A). This enables using satellite data to reveal the methane seepage zones at the sea surface if the gas flux will be continued to emanate from the seabed to the surface of water column.

As a result of this study it was performed the monitoring and analysis of MODIS images (MOD021KM) for 2000-2003. The most attention was paid to the satellite images acquired for 2000. At the same time the higher seismic activity in the Black Sea region was observed and induced the gas methane emissions of the certain volume at the test site. The earthquakes of magnitude 5.0 and 6.0 on the Richter scale, which occurred in Romania and Turkey in 12.05.2000 and 5.10.2000, respectively, have influenced just on the tectonic conditions in the north-western Black Sea at the investigated area of the Dnieper paleodelta.

The study has resulted in the detection the anomalies on the images for the investigated area and they have been interpreted as methane seeps, and some of them are shown in Fig. 4. (Quick Looks): a, b, c – from the satellite Terra (ascending orbit) and Fig. 4.: d, e, f – from the satellite Aqua (descending orbit). As far as the spatial position of the anomalies they are slightly shifted, however test site (with the coordinates of gas seeps) remains within the boundaries of revealed anomaly cloudiness. In this case it needs to take into account of the action of marine currents (Fig. 5), which are circulated in this region as well as the weather conditions.

Operational efficiency and coverage of the significance areas due to monitoring using satellite images provide the detection of the anomaly spots and the periodicity of their appearance that is interpreted as methane seeps at the sea surface in the investigated area according geological and geophysical conditions as well as weather, hydrological and other factors of influence.

Occurrence of above mentioned anomalies within the investigated area are connected with the periodical gas methane emanations that once again conforms the prospectively for gas accumulation (gas methane discharging at this area) and can serve as the prerequisite for gas extraction, of course, taking detail geological, geophysical and lithological studies, possibly with the drilling of the exploratory well. As a rule, it requires the additional costs, but the experience of foreign geologists and the results of their studies (Fujii et al., 2015; Yamamoto, 2015)

show that in the future the suitability assessment for methane extraction from the gas hydrates deposits can be carried out. It is known that gas hydrates formation in the lithological thickness occur by the accumulation of methane, which don't rise to the sea surface. This feature is connected with the boundary

of hydrate stability, whereas methane seepage takes place in the unconsolidated rock zones, namely in the zones of tectonic disturbances, which are observed in the seabed relief, in this case it is the Dnieper paleodelta.

Fig. 4. MODIS scene fragment (Quick Look) with the cloud accumulations over the methane seepage of the test site. Explanation: *a.* Survey performed on 3rd March, 2000, 9:20; *b.* Survey performed on 3rd July, 2000, 8:20; *c.* Survey performed on 13th July, 2000, 8:55; *d.* Survey performed on 8th May, 2000, 20:15; *e.* Survey performed on 14th May, 2000, 19:40; *f.* Survey performed on 13th May, 2000, 20:35.

Fig. 5. Sea currents in the Black Sea and the Sea of Azov (Igor Smahin, 2005; sites.google.com).

Conclusions. As a result of this study methane seeps were revealed and indentified on the MODIS images as cloudiness or its lack at the background of cloud cover over the test site near the Dnieper paleodelta in the Black Sea, where there are the known fluid emission accumulations of gas methane, found by geological and geophysical methods. This allows using image analysis for the future studies of gas emanation from seabed taking into account geological information and additional hydrological and meteorological data.

The analysis of the images has shown that the period of higher seismic activity in this region (in particular, influence of the Vrancea zone) effects tectonic conditions directly in the north-western Black Sea and causes the increase of methane emission of the seafloor that is detected by MODIS sensor and observed on the satellite images.

The phenomenon of anomaly cloudiness on the images over the investigated area is explained by the temperature difference induced the methane rising from seafloor to sea surface and further to troposphere. This rising methane is cooler than the sea surface water and warmer than the layers of atmosphere that provokes the formation of condensed vapor in the form of scattered clouds over the test site with the methane seeps. This phenomenon is identified on the satellite images in the clear weather. And conversely, when the meteorological conditions change forming rain cloudiness with the abrupt temperature drop in comparison with surroundings, the volume of gas methane is considerably warmer and disperses clouds forming the area without clouds at the background of dense cloudy cover. This phenomenon is detected in the different spectral (thermal and infrared) ranges of the NASA satellites (MODIS, NOAA, etc.) and connected with the properties of methane (Bashin, 2010), which rising into

low layers of atmosphere absorbs intensively thermal emission of the Earth in the IR range at the wavelength of 7.66 μm .

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