The goal of the project is to assess changes in the environmental condition of the Caspian Sea during the current century under the influence of natural and anthropogenic factors. To solve this problem, a detailed analysis of large banks of satellite data acquired over the Caspian for the period from 1999 to 2022, together with long-term hydrometeorological data is required.

The solution of the task set in the project became possible exclusively thanks to the creation at IKI RAS of the See the Sea (STS) information service, which is an integral part of the "IKI-Monitoring" center for collective use. STS provides researchers engaged in studying the seas and oceans with a constantly expanding toolkit for working with remote sensing data, thus making it possible to comprehensively analyze satellite data various in their physical nature, spatial resolution, dimensionality and time of acquisition. It is important to note that the implemented technologies provide an opportunity to study both spatial and temporal, including long-term, dynamics of phenomena and processes in the seas and oceans.

Multifactor analysis of the environmental state of the Caspian Sea is performed for the first time for the entire Caspian Sea water area with use of multi-sensor and multi-platform satellite remote sensing data, which defines the scientific novelty of the project.

The work carried out in 2021 and the main results obtained are described below.

In the See the Sea (STS) information system, the completeness of satellite data archives for 2014-2018, necessary for the work on the project, was checked. There were 151 cases of missing data for some months of 2014-2016, when the corresponding metadata were available. In order to replenish the archives, a request was prepared for the representatives of the "IKI-Monitoring" center, which was promptly fulfilled.

Проведен отбор новых для исполнителей проекта и представителей ОИ ЦКП «ИКИ-Мониторинг» данных спутников PlanetScope, имеющих пространственное разрешение 3 м, предоставляющих информацию в оптическом диапазоне. Налажено их автоматическое интегрирование в архивы STS, освоена работа с новыми данными и их совместное использование с уже имеющими архивами STS. Все полученные результаты внесены в ИС STS, которая является составной частью ОИ ЦКП «ИКИ-Мониторинг». На основе проведенного анализа были решены следующие задачи.

The data from the PlanetScope satellites having spatial resolution of 3 m and provide information in the optical range was new to both the project executors and representatives of the IPC "IKI-Monitoring". The data has been selected for processing. Their automatic integration into the STS archives was implemented, the work with the new data and their joint use with the already existing STS archives was provided. All the results obtained were stored in the STS IS, which is an integral part of the "IKI-Monitoring" center. Based on the analysis performed, the following tasks were solved.

1. During the third phase of the project work, using the cartographic interface integrated into the STS system, detailed maps of oil pollution of the sea surface detected by satellite data for 2014-2018 and 2021 in the areas of the most intensive pollution of the sea surface were made: (i) the Oil Rocks oil production area, where the main sources of pollution are oil field exploration and exploitation; (ii) part of the Caspian Sea water area east of Cape Sefid Rud and part of the Caspian Sea water area west of the Cheleken Peninsula, where oil hydrocarbon release points from the sea floor were identified; (iii) the South Caspian Basin, where numerous surface oil manifestations are due to mud volcanism on the sea floor. In addition, a map of pollution of the sea surface by oil-containing films as a result of discharges of polluted water from ships was made.

The distributions of areas of individual oil contamination of the sea surface in different test areas have been calculated. It has been determined that the individual sizes of slicks of natural oil occurrences on the sea surface in the Oil Rocks area, and in the areas of underwater sips near Cape Sefid Rud and Cheleken Peninsula may differ by an order of magnitude.

The inter-annual variability of the area potentially exposed to oil film pollution in different sites has been determined. The annual total area of oil pollution of the sea surface due to seepage of hydrocarbons from the seabed, calculated using satellite data for three areas of sustainable pollution, varies in the range from 2404 sq. km to 6615 sq. km.

The fact of seasonal variability in the number of natural oil manifestations on the sea surface detected on satellite images has been proved, especially significant for the data obtained in the visible range.

The relative contribution of each type of pollution to the integral oil pollution of the Caspian Sea surface in 2014-2018 and in 2021 was assessed. It was found that the main contribution is made by continuous oil pollution of the sea surface in the area of the Oil Rocks ─63%, as well as mud volcanic activity on the seabed in the area of the South Caspian depression ─ 20%. Natural oil manifestations of hydrocarbons from the seabed contribute less to the total picture of pollution ─ 17% in total. Unauthorized discharges of oil-containing films from ships are not the main source of film pollution of the sea surface, but they also contribute to the integral oil pollution of the Caspian Sea surface and must also be taken into account for the assessment of the environmental condition of the whole water area.

The frequency and intensity of mud volcanism and natural seepage of hydrocarbons from the seabed to the sea surface were estimated in 2014-2018 and in 2021. A unique data set of SLSTR Sentinel-3A, -3B satellite radiometers recorded the eruption and subsequent release of mud volcano near the eastern coast of Azerbaijan on the uninhabited island Dashly on the July 4th, 2021. Further development of the situation was tracked on the basis of data in various ranges of the electromagnetic spectrum, received by sensors MODIS Terra, MSI Sentinel-2, SAR-C Sentinel-1A and KMSS "Meteor-M" № 2. As satellite radar images obtained before and after the mud volcano eruption showed, the area of Dashly Island increased after the explosion 2.4 times from 0.0904 sq. km to 0.22 sq. km.

2. Based on the analysis of multi-year satellite data series, both high and medium resolution, obtained over the water areas of the Southern and Middle Caspian Sea for 2014-2018 and 2021, maps of regular phytoplankton blooms have been made for the Caspian Sea during the study period, supplemented by areas of increased values of chlorophyll-a concentration, identified by MODIS data.

The characteristics of interannual, seasonal and spatial variability of phytoplankton bloom in 2014-2018 and in 2021 were obtained. It was found that a negative trend in chlorophyll-a concentration values was observed in the Northern Caspian, intensifying from 2019 till first half of 2021. In the Middle Caspian a slight positive trend was observed in 2014-2018, which changed to a negative trend in 2019 to June 2021. The only difference is in the average values of chlorophyll-a concentration. The maximum monthly average values do not exceed 4.5 mg/m3, and there is a negative trend in 2019-2021. The values given were estimated for the entire water area of each site, but the values were significantly higher in the coastal zones. Both in the Middle and South Caspian they could reach 20 mg/m3. Not counting the Northern Caspian, the highest values of chlorophyll-a concentration were observed in the area of the Apsheron Peninsula.

3. Characteristics of interannual variability and trends of the main hydrometeorological parameters of the Caspian Sea for 2014-2018 and 2021 were obtained. It was found that over the past three years, the sea

surface temperature increases in all areas of the Caspian Sea, and the amount of atmospheric precipitation decreases. The largest negative trend in the amount of atmospheric precipitation from July 2000 to December 2020 according to NASA Giovanni was observed for the Middle Caspian. It was equal to -0,3 mm/month/year, which is an order of magnitude higher than previously determined for the period 1979-2010. (-0.01 mm/month/year). In the South Caspian, on average, the trend of precipitation was close to zero.

4. The main characteristics of the ice cover in the Northern Caspian Sea, such as: winter severity index; duration of the ice cover; maximum area of the ice cover were estimated. The schematic maps of the ice cover in the Caspian Sea for the winter periods of 1999-2020, based on the satellite data, have been made earlier and supplemented with the information about the maximum ice cover extent in the winter period of 2020/2021. In 2021 the winter severity index was calculated not from data of the coastal weather stations, but from data of MERRA-2 reanalysis (NASA Giovanni system source). For the entire water area of the Northern Caspian Sea the sum of negative air temperatures during the winter was -585 degrees, which corresponds to an average winter severity. The duration of the ice cover in the eastern part of the Northern Caspian Sea was 128 days, and the maximum area in the entire water area of the Northern Caspian Sea - 75 thousand square kilometers.

5. Schematic maps of the elements of the Caspian Sea water circulation identified by satellite radar and optical data for 2014-2018 and 2021 were made: vortex structures, internal waves, run-up and upwelling phenomena influencing the transfer of pollution. For each part of the Caspian Sea the main vortex formation areas have been identified. By now we have an idea of the character of vortex formation and its surface manifestations in the Caspian Sea since 1999 up to present time.

The plume boundary maps of the Sulak River (Dagestan) were made based on high spatial resolution optical data for 2016-2021. The largest plume areas are observed in May-early June and can reach 90 sq. km. In 2021, on May 20-23, sub-satellite measurements of the Sulak River plume parameters were carried out, which showed that the turbidity values with implicit plume reached 60 NTU near the mouth. The plume boundary was located no further than 3 km from the coast. The velocity of spreading of the boundary of the plume front was estimated, which was 4 cm/s. This makes it possible to carry out sub-satellite measurements not strictly synchronous with the satellite imagery, since the plume position does not change rapidly during the day.

6. The "See the Sea" information system was improved to develop a new toolkit for solving tasks arising in the course of the project. The development of the specialized database for phenomena information resulted in integrated with the technology of building distributed archives of satellite data UNISAT. Thus, the information about the sea surface phenomena detected becomes a part of satellite imagery metadata attributes. This makes it possible to use the detected phenomena as a criterion for image retrieval in the archives.

The results of work on the project are presented in 6 publications indexed in the databases SCOPUS, Web of Science, as well as presented at five conferences:

The materials concerning this project can be found on the website http://www.iki.rssi.ru/asp/dep_proj/proj_20060.htm.