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Spatial-Temporal Variability of Small Gas Impurities over Lake Baikal during the Forest Fires in the Summer of 2019

Galina Zhamsueva *, Alexander Zayakhanov, Vadim Tcydypov, Ayuna Dementeva and Tumen Balzhanov

Institute of Physical Materials Science Siberian Branch, Russian Academy of Sciences, 670047 Ulan-Ude, Russia; azayakhanov@gmail.com (A.Z.); tsydypov.vadim@gmail.com (V.T.); ayunadem@gmail.com (A.D.); tbalzhanov@gmail.com (T.B.)

* Correspondence: Lrf@ipms.bscnet.ru; Tel.: +7-30-1243-4664

Abstract: Lake Baikal—a unique ecosystem on a global scale—is undoubtedly of great interest for a comprehensive study of its ecosystem. In recent years, one of the most significant sources of atmospheric pollution in the Baikal region was the emission of smoke aerosol and trace gases from forest fires, the number of which is increasing in the region. The transport and accumulation of aerosol and small gas impurities over water area of Lake Baikal is observed every summer due to forest fires occurring in the boreal forests of Siberia. The atmosphere above the lake covers a huge area (31,500 km^2) and is still a little-studied object. This article presents the results of experimental studies of ground-level ozone, sulfur dioxide, and nitrogen oxides in the atmosphere over Lake Baikal, carried out on a research vessel during the boreal forest fires in Siberia in the summer of 2019.

Keywords: Lake Baikal; ground-level ozone; nitrogen oxides; sulfur dioxide; forest fires; research vessel "Academik V.A. Koptyug"

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1. Introduction

All fresh-water ecosystems are exposed to the stress inherent in a complicated system of changes in the climate of the planet [1]. Lake Baikal—a unique ecosystem on a global scale—is undoubtedly of great interest for a comprehensive study of its ecosystem. The principal reasons for choosing Baikal as a natural laboratory to study global climate change are determined by the unique properties of the Baikal ecosystem.

The atmosphere over Lake Baikal covers a vast area (31,500 km^2) and has more significant differences in the composition and variability of gaseous and aerosol components in atmospheric air than in coastal continental areas and is still a poorly studied object. In the zone of atmospheric influence of Lake Baikal are large industrial centers and settlements of the Baikal and Trans-Baikal, which are distributed very unevenly along the coastal zone. The spatial and temporal variability of anthropogenic impurities over the Baikal is largely formed under the influence of outflows from these territories, i.e., it is determined by the geographical distribution of continental sources and the prevailing circulation of air masses in a particular area [2–5].

With increasing anthropogenic and natural impact on the atmosphere of the lake the study of the background characteristics of atmospheric pollutants is becoming relevant and becomes important. In the atmosphere of the Baikal basin, there are many factors that affect natural complexes, but the most significant in recent years have been forest fires, which cause damage not only to nature, but also to the economy of the region. Assessment of environmental damage to the ecosystem of Lake Baikal is still an unsolved problem due to the increasing anthropogenic load and extreme natural events, such as forest fires, because of insufficient data on the composition of chemically active gas components, aerosols, considering various factors that affect the composition and quality of atmospheric air. In this regard, the study of spatial and temporal variability of the composition and properties of the atmosphere, assessment of the transboundary contribution of pollutants, their forecast, as well as a clear definition of their possible consequences for the environment of Lake Baikal, is currently an urgent scientific problem.

In contrast to the Baikal region, there is a lot of research that has been done to study the quantitative and qualitative composition of atmospheric air in North America and Europe, including the European part of Russia [6–13]. In the Baikal region, there are few such studies, and they are different because there is no integral program for monitoring air pollution that meets modern requirements. At present, the experimental research of quantitative and qualitative composition of atmospheric impurities are mostly episodic. Basically, research is carried out in an expedition in the summer with the participation of scientific teams of the Siberian Branch, Russian Academy of Sciences (Institute of Physical Materials, V.E. Zuev Institute of Atmospheric Optics, Limnological Institute). The most complete studies have been conducted on the chemical composition of atmospheric precipitation in the Baikal region in the seventies of the last century [14,15]. It is established that in the last decade, the chemical composition of atmospheric precipitation in the Baikal region has undergone qualitative changes: the total salt content has decreased, and the acidity of precipitation has increased. Currently, the physical and chemical properties of atmospheric aerosol are being studied [16–18]. Since 1999, the program of long-term continuous monitoring of atmospheric precipitation under the EANET international program has been operating at three stations in the Baikal region [19]. The results of experimental studies of the distribution of small gas impurities and aerosols in the lake area show that the southern part of Lake Baikal is most susceptible to pollution [20–24]. The important role of breeze circulations in daily variations of ozone and other small gas impurities near the coastal zone of Lake Baikal is revealed. Breeze circulations significantly affect the transport and dispersion of atmospheric impurities in the region [25].

According to experts, about 20% of annual emissions from biomass burning in the world are accounted for by forest fires occurring in the boreal regions of Russia, Canada, and Alaska [26]. According to satellite observations, fires occur annually on an area of 10–14 million hectares and in the forest and forest-steppe zones of Siberia [27]. Air quality impacts from forest fires are not only due to emissions of primary pollutants such as greenhouse gases, photochemically active compounds, and small and large particulate matter, but also due to secondary pollutants (e.g., ground-level ozone O_3, secondary organic aerosol (SOA)). These emissions significantly affect the chemical composition of the atmosphere and the Earth's climate system. Fires are a major source of ozone precursors, such as nitrogen oxides and non-methane organic compounds [28].

The transfer and accumulation of aerosol-gas impurities in the water area of Lake Baikal is observed every summer due to forest fires occurring in the boreal forests of Siberia. In the summer of 2019 in Eastern Siberia, there were extreme fire-weather conditions with the most large-scale forest fires in the last 20 years, which lasted from June to September [29]. So, in July 2019, the scale of the catastrophe from forest fires in Siberia amounted to about 3 million hectares, the main centers were located in the Krasnoyarsk region, Irkutsk region and the Republic of Sakha (Yakutia). According to the FBU Avialesohrana, as of 31 July 2019, there were 140 forest fires in the Irkutsk region on an area of about 709 thousand hectares, in the Krasnoyarsk territory—110 seats of fire on an area of about 1.06 million hectares, in Yakutia—139 forest fires on about 1.14 million hectares of land [30]. By mid-August, the area of forest fires reached a record 5 million hectares. With the prevailing east wind direction, air smoke was observed in Western Siberia, Kazakhstan, and the Arctic. Despite the significant number and scale of annual forest fires in Siberia, scientific publications on studies of their emissions and estimates are extremely limited [31].

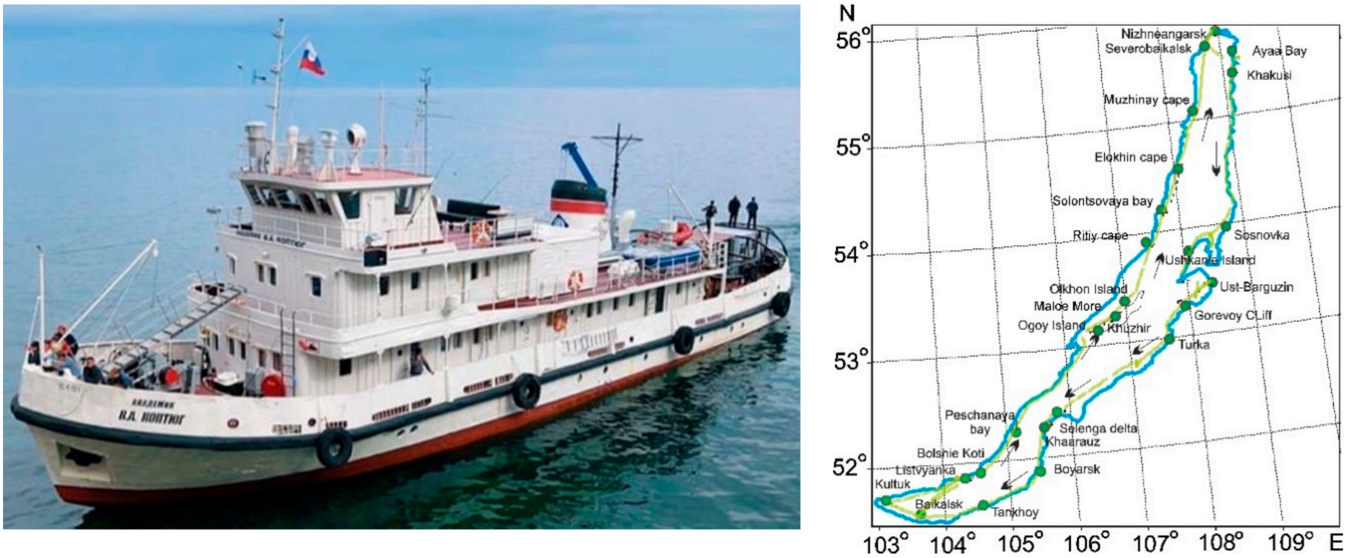
Nature conservation of Lake Baikal, as a World Heritage Site, has received more and more attention in recent years. One of the important channels for the entry of pollution into the lake basin is the atmosphere. The real-time observation monitoring can provide the most complete information for assessing the current state of the air basin [32]. However, observations of individual components of the aerosol and gas composition of the atmosphere are currently conducted only at coastal "continental" stations and only occasionally from a ship [2,23,24].

In the summer of 2018, for the first time, we carried out targeted studies of gaseous impurities in the drive layer of Lake Baikal on the science research vessel (SRV) "Academik V.A. Koptyug" during the forest fires in Siberia. The highest concentrations of gaseous impurities were found in the near-water atmosphere of the river Selenga River delta, Barguzinsky Bay, Peschanaya Bay. A sharp increase of sulfur dioxide concentration (SO_2) up to 40 µg m^{-3} and concentration of nitrogen dioxide (NO_2) up to 30 µg m^{-3} was noted when approaching Peschanaya Bay, to places of rest for tourists, and the maximum values of SO_2 (60 µg m^{-3}) were observed during anchorage in the bay [33,34]. During the period of the ship expedition (15–26 July 2018), continuous synchronous observations of the concentration of ground-level ozone (O_3), sulfur dioxide, meteorological parameters of the atmosphere were carried out at the Boyarsky scientific station located on the southeastern coast of Lake Baikal. When comparing the concentrations of ground-level ozone as a secondary pollutant, measured simultaneously under similar meteorological and weather conditions at the Boyarsky station and in the water area of Lake Baikal, good agreement was noted in the behavior of ozone in the time interval as a whole, including its short-term variations, despite the fact that ground-based and route measurements of the temporal variability of ozone are separated in space. We can also note a good coincidence of daily maxima in the ozone distribution, both in concentration levels and in the observation time. In general, judging by the O_3 distribution in Boyarsk and in the water area of Lake Baikal, it can be concluded that the air flows on Lake Baikal are well mixed.

In 2019, our investigations were continued on the lake's water area with the help of a research vessel, aimed at analyzing and assessing atmospheric pollution over Lake Baikal during a fire hazardous summer period.

2. Methods and Materials

The route of the science research vessel "Academik V.A. Koptyug" took place along the entire perimeter of Lake Baikal from 24 July to 4 August, 2019 (Figure 1a). The Circum-Baikal map of the expedition route 2019 on the science research vessel is shown in Figure 1b. The beginning and end of the route was the port of Listvyanka. Initially, the vessel headed north along the perimeter of Lake Baikal. The vessel moved along the coast at a distance from 30 m to 5 km. The total length of the route was ~1700 km. In the Figure 1b, arrows indicate the vessel's route. The coordinates of the measurement points were determined by the ship's GPS system.



(**a**) (**b**)

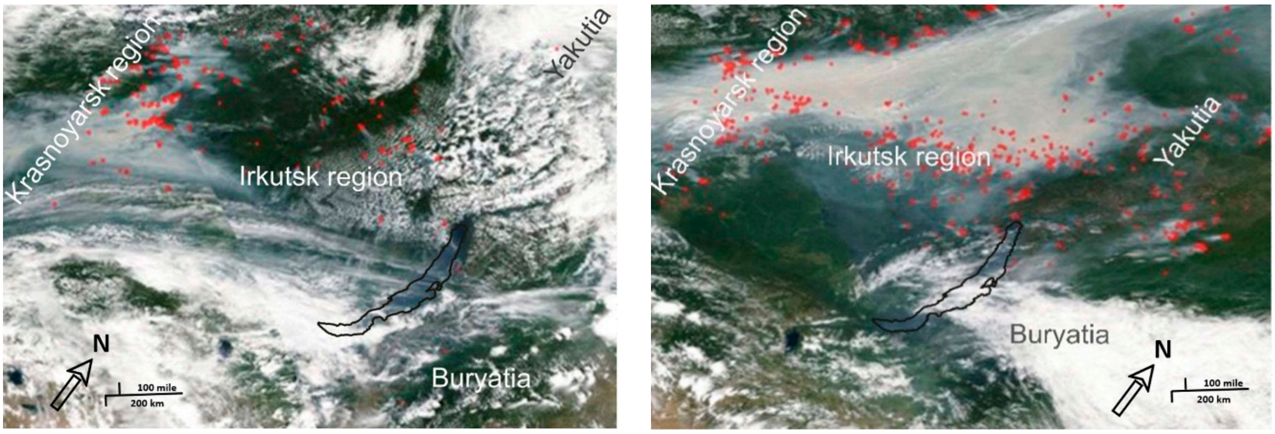
Figure 1. The scientific research vessel "Akademik V.A. Koptyug" (**a**); schematic map of the vessel's route (**b**).

The set of equipment for measuring the gas composition of the Baikal drive layer was installed in the lower deck of the vessel to exclude the influence of the ship's emissions, the acoustic meteorological complex "AMK-03" [35] was installed on the upper deck of the vessel. Air samples for gas-aerosol instrumentation were taken using Teflon pipes at an altitude of 6 m above the water surface. The 3.02 P-A, P-310A, C-310A chemiluminescent gas analyzers (OPTEK Inc., St. Petersburg, Russia) were used to measure the small gas impurities such as the concentrations of ozone, nitrogen oxides, and sulfur dioxide. The P-310A and C-310A gas analyzers measured the concentrations in the range from 0 to 1000 μg m^{-3} with an error of ±25%, and the 3.02 P-A gas analyzers in the range from 0 to 500 μg m^{-3} with an error of ±20%. Calibration and zeroing were performed automatically with the help of built-in microflux sources according to commands from gas analyzers' processor. The gas analyzer measurement accuracy is controlled using Mod. 8500 Monitor Labs calibrator (Monitor Labs. Inc., United States).

General synoptic processes over the region were analyzed on the basis of surface weather maps from Arctic and Antarctic Research Institute [36]. To analyze the transport of smoke aerosol and its spatial distribution on a regional scale, the data obtained from the MODIS (Moderate Resolution Imaging Spectroradiometer) [37] and CALIPSO (The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) [38] satellites were used, and the paths for the transfer of air masses trajectory were calculated at three altitude levels: 100, 500, and 1000 m using the HYSPLIT (The Hybrid Single-Particle Lagrangian Integrated Trajectory model) trajectory reanalysis model and archival meteorological data of the National Oceanic and Atmospheric Administration (USA) [39].

3. Results and Discussion

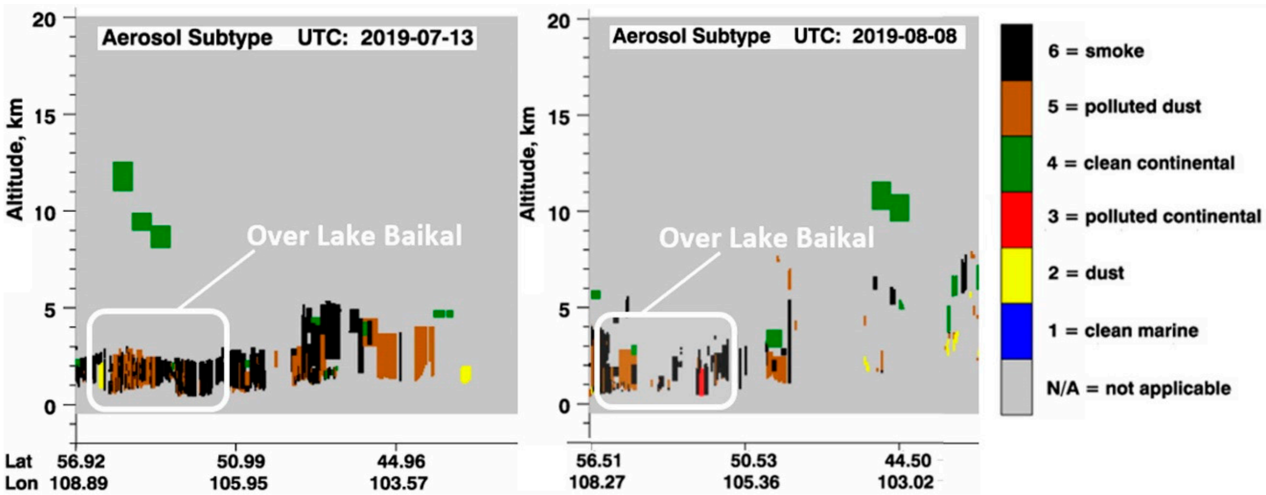
In the summer of 2019, large-scale forest fires were observed in the Irkutsk Region, Krasnoyarsk Region and Yakutia. According to MODIS satellite observations, the smog from forest fires since the end of July has spread throughout the water area and the coast of Lake Baikal. Figure 2 shows images of atmospheric smoke in the Baikal region from forest fires on 13 July and 7 August 2019. The vertical movements arising from fires raise significant masses of warm air in convective structures to high altitudes. It makes it possible for them to spread in the upper layers over large areas.



(**a**) (**b**)

Figure 2. Satellite images of atmospheric smoke over Lake Baikal, July–August 2019 (MODIS): (**a**) 13 July 2019; (**b**) 7 August 2019.

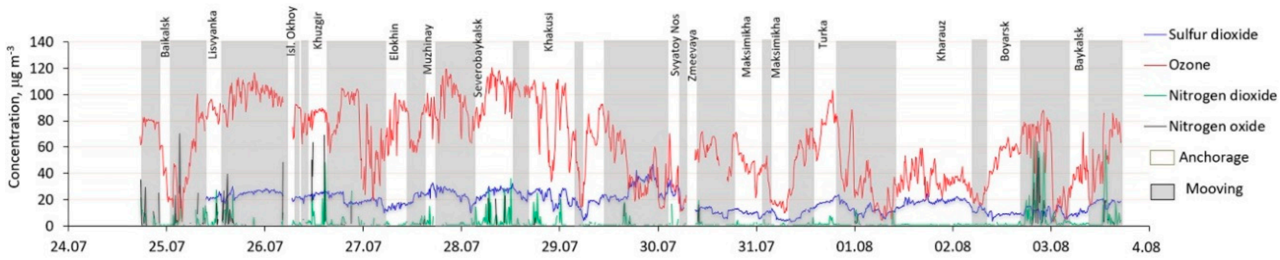
In order to study the distribution of the dominant aerosol components over the Baikal region in the summer of 2019, the results of measurements of vertical profiles of the parameters of suspended particles by the space-based CALIOP lidar on the CALIPSO satellite were analyzed. A spatial section of the vertical atmospheric depth in units of weakened aerosol backscattering showed that in July–August 2019 over Lake Baikal, on some days, a homogeneous filling of the atmospheric layer with smoke aerosol up to 3–4 km was observed (Figure 3).



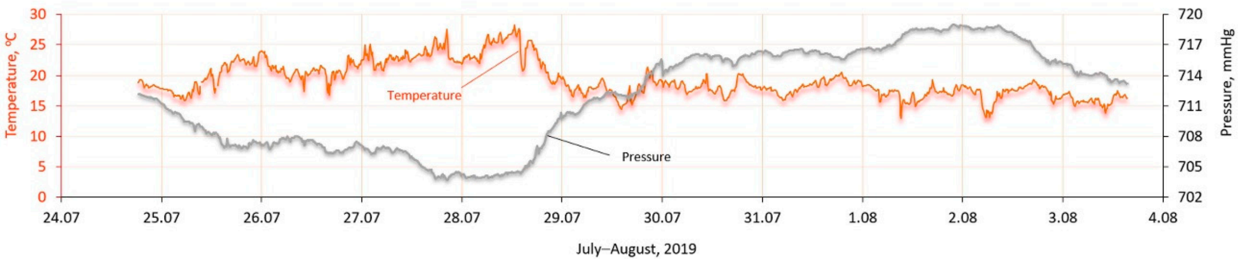
(**a**) (**b**)

Figure 3. The plot of CALIPSO aerosol vertical profile. The X axis—latitude and longitude, the Y axis—altitude, the colors scale—type of aerosol. (**a**) aerosol subtype, UTC: 2019-07-13; (**b**) aerosol subtype, UTC: 2019-08-08.

Figure 4 shows the experimental data on the spatial–temporal distribution of the concentration of ozone, sulfur dioxide, nitrogen oxides, meteorological parameters (temperature, pressure) along the route of the vessel over water area of Lake Baikal in a 10-min measurement interval. The spatial–temporal variability of O_3 and small gas impurities (NO_2, SO_2) is extremely heterogeneous over the lake's water area. Both extended areas with an increased content of O_3, SO_2, NO_2, and separate local outbreaks are distinguished.



(**a**)

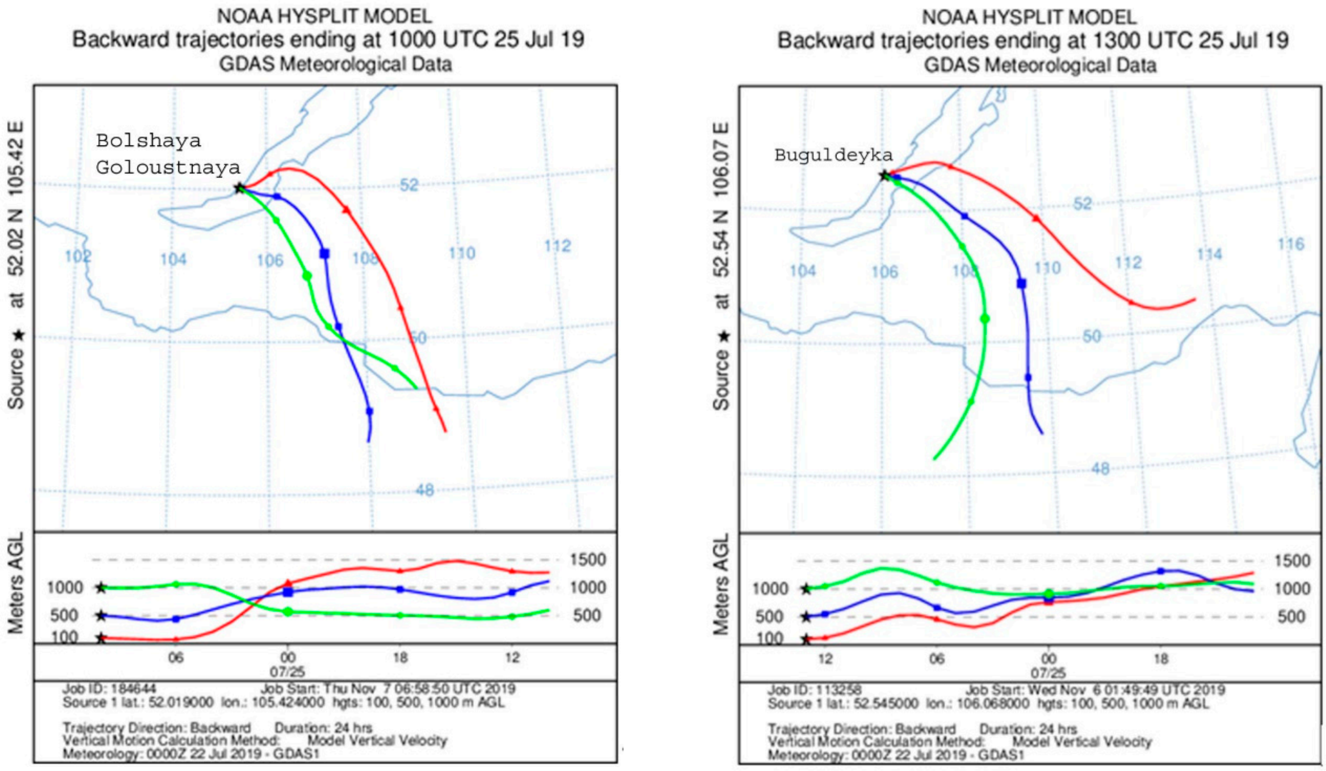


(**b**)

Figure 4. The spatial—temporal variability along route of the research vessel "Akademik V.A. Koptyug": (**a**) round-level of ozone, nitrogen dioxide and sulfur dioxide concentrations; (**b**) temperature, pressure.

At the beginning of the route measurements on 24 July, the region of South Baikal was under the influence of a low-gradient low-pressure baric field. The direction of air flows was predominantly southeast according to the data of the State Scientific Center of the Russian Federation the Arctic and Antarctic Research Institute [36]. From the next day, 25 July, a displacement of the formed cyclone center to the southeast was observed, which continued in the following days until 28 July due to its displacement by the southwestern branch of the anticyclone. Under the conditions of the formation of a stable air mass in the warm sector of the cyclone, high daytime air temperatures were observed up to 25 °C and higher. At the same time, high concentrations of ground-level ozone were noted up to 120 μg m^{-3}. During this period, increased concentrations of sulfur dioxide were also observed with maximum daily concentrations up to 30 μg m^{-3}, but the concentrations of nitrogen oxides (NO, NO_2) did not exceed the background values. During the measurement period from 24 July to 29 July, when high levels of sulfur dioxide were noted, the direction of air flows to the lake's water area was east, south-east, and north-east. An analysis of the backwards trajectories of air masses according to the HYSPLIT model shows that the drift of air masses into the area of the ship passage occurred from the territories where large settlements and industrial centers of the Republic of Buryatia are located, such as Ulan-Ude, Gusinoozersk, Kamensk, Selenginsk, Timlyui, Kabansk.

In Figure 5 shows the backwards trajectories of air mass transfer for the periods corresponding to the passage of the vessel near the settlements Bolshaya Goloustnaya (Figure 5a) and Buguldeika (Figure 5b), located on the southwestern coast of Lake Baikal.



(**a**) (**b**)

Figure 5. Backwards trajectories of air masses transfer according to the HYSPLIT model: (**a**) Bolshaya Goloustnaya; (**b**) Buguldeika. The paths for the transfer of air masses trajectory at three altitude levels: 100 m (red color), 500 m (blue color) and 1000 m (green color).

In the Lake Baikal region, one of the major sources of sulfur dioxide emissions is the Selenginsky pulp and cardboard mill, where the production of sulphate unbleached cellulose is accompanied by emissions of both basic and specific pollutants containing sulfur (dimethyl sulfide, methyl mercaptan, sodium sulfate, carbon disulfide). Although the main inputs of sulfur compounds into the troposphere are associated with anthropogenic sources, there are also natural sources of sulfur dioxide input into the atmosphere. So, in the area of the Selenga delta there are vast swamps, which are a source of hydrogen sulfide. With the participation of free radicals, hydrogen sulfide in the atmosphere, as well as dimethyl sulfide, is oxidized sequentially in several stages to sulfur dioxide:

$$H_2S + OH^- \rightarrow HS + H_2O \quad (1)$$

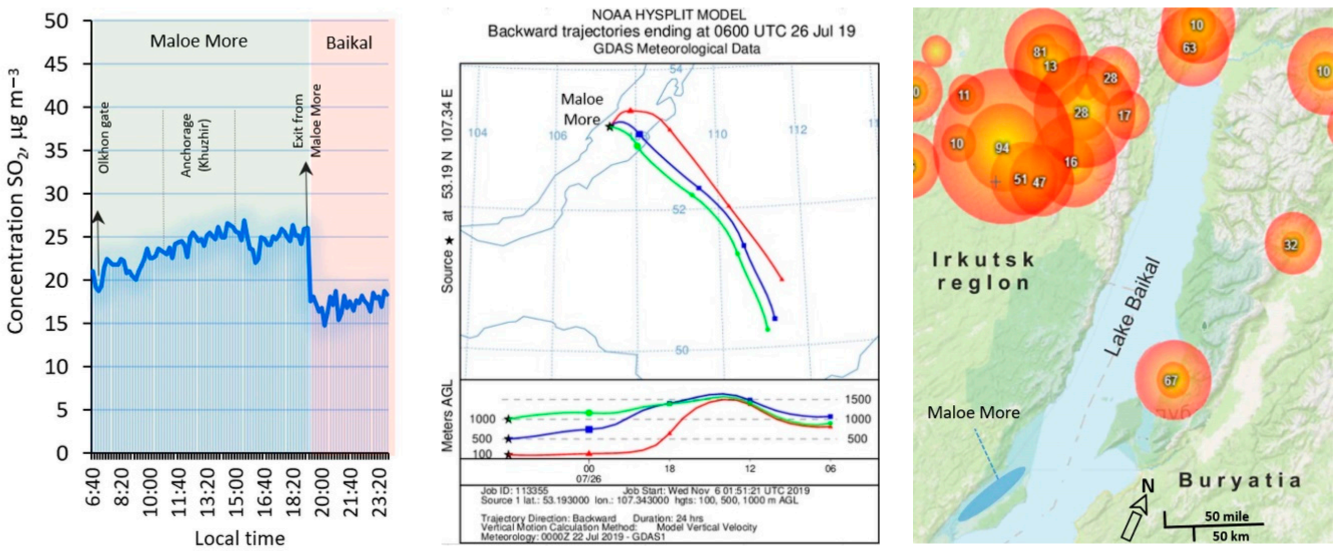
$$HS + O_2 \rightarrow OH^- + SO \quad (2)$$

$$SO + HO_2 \rightarrow SO_2 + OH^- \quad (3)$$

As is known, in the zone of pine forest contamination with industrial emissions containing sulfur dioxide, in two-year-old pine needles, an increased sulfur content is accumulated due to the absorption of SO_2 from the atmospheric air in comparison with the control samples, namely, up to 0.137% based on dry matter weight [40]. Sulfur-containing compounds accumulated in forest and soil vegetation enter the atmospheric air during fires in the form of sulfur dioxide, the lifetime of which is 2–5 days [41]. The distance of its transfer from the source can be more than 500 km, with an average wind speed of 3–4 m/s and the lifetime by SO_2 in the atmosphere for 2 days [42]. Most of the sulfur dioxide is concentrated in the lower near-surface layer of the atmosphere, since it is about twice as heavy as air. Consequently, in the water area of Baikal, the accumulation of sulfur dioxide is possible due to temperature inversions when the lower temperature of the water surface in comparison with the surrounding air and the poor solubility of sulfur dioxide in water are observed. Usually the concentration of SO_2 changes much more slowly than the concentration of water vapor [43].

Despite the observed high concentrations of SO_2 along the Listvyanka-Khuzhir route (Olkhon Island), the concentrations of nitrogen oxides (NO, NO_2) remained at the background level (3–7 µg m^{-3}) (Figure 4a), although their concentrations usually increase synchronously with SO_2 concentrations. It is known that the rate of NO_2 oxidation is five times higher than that of SO_2, that is gaseous nitrogen oxides are transformed into nitrates faster than sulfur dioxide into sulfates [44]. Therefore, the absence of nitrogen dioxide at high concentrations of SO_2 may mean that, possibly, the detected plume of SO_2 pollution near the southwestern coast accumulated for a rather long time (up to several hours), and gaseous nitrogen oxides had time to oxidize to nitrates. Due to the higher oxidation rate of NO_2 as compared to SO_2, lower concentrations of nitrogen oxides or their complete absence are recorded (Figure 4a). Similar results were noted in [45] during the period of experiments on Lake Baikal.

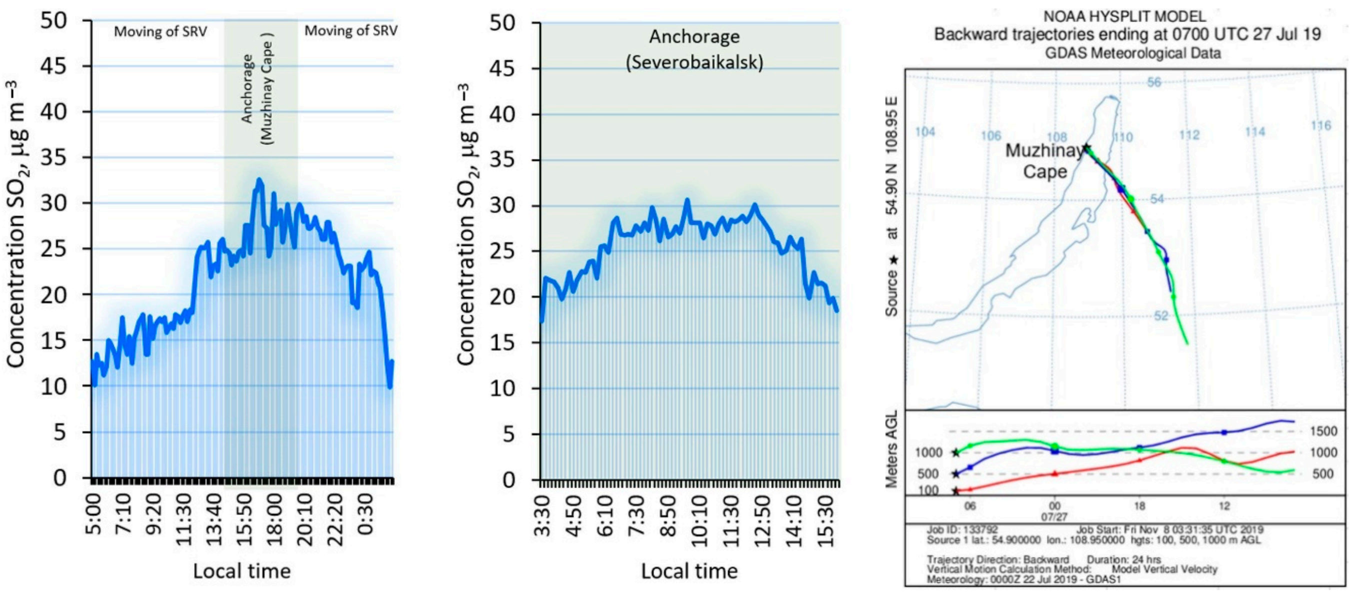
An increase in the concentration of sulfur dioxide SO_2 up to 28 µg m^{-3} was noted as the research vessel approached the settlement of Khuzhir in the Maloe More on 26 July, which significantly exceeded the background concentrations (Figure 6a). On average, the concentration remained high, right up to the exit from the Maloe More. In the behavior of sulfur dioxide there was noted no noticeable changes during the passage of the ship in the immediate vicinity. Figure 6b shows the results of calculating the backwards trajectories of air mass transfer (HYSPLIT), maps of the pyrogenic situation [31] in this area (Figure 6c), which indicate the drift of smoke gases from the nearest forest fires center in the Barguzinsky Nature Reserve on the northeastern coast of Baikal and in the north of the Irkutsk region. After the research vessel left the Maloe More for the open Baikal, the concentration decreased by 12 µg m^{-3} (Figure 6a).



(**a**) (**b**) (**c**)

Figure 6. Temporal variation of the concentration of sulfur dioxide in the water layer of Lake Baikal during of 26 July 2019 (**a**); backwards trajectories of air masses according to the HYSPLIT model (**b**); the paths for the transfer of air masses trajectory at three altitude levels: 100 m (red color), 500 m (blue color) and 1000 m (green color); map of fires in the northern part of Lake Baikal for this period (**c**). The number of fires is indicated in the center of the circle.

Furthermore, during the passage and anchorage of the research vessel near Cape Muzhinay, when the wind direction changed to the south, from the southeast, a sharp increase in the content of sulfur dioxide was observed up to 32 μg m^{-3} (Figure 7a). Analysis of backwards trajectories of air mass transfer trajectories (HYSPLIT) during this period indicates that the main contribution to the increase in SO_2 content was made by the forest fires in the area of Sosnovka on the northeastern coast of Lake Baikal (Figure 7c). In the north of Baikal, the main contribution to the increase in the SO_2 content in the atmosphere was also made by closely located forest fires center in the Sosnovka area. The presence of smoke aerosol over Lake Baikal during this period was also observed visually, a high content of sulfur dioxide and ozone in the water layer persisted throughout the day along the vessel's route in the north of lake (Figure 4a).



(**a**) (**b**) (**c**)

Figure 7. Temporal variation of concentration of sulfur dioxide in the Lake Baikal water layer: Cape Muzhinai (27 July 2019) (**a**); Severobaikalsk (28 July 2019) (**b**); backwards trajectories of air masses transfer (28 July 2019) the paths for the transfer of air masses trajectory at three altitude levels: 100 m (red color), 500 m (blue color) and 1000 m(green color) (**c**).

When the research vessel passed near the Sosnovka Bay on 29 July, the highest concentrations of SO_2 along the entire route were observed up to 47 μg m^{-3} due to the proximity of forest fires (Figure 8). Under the conditions of smoke outflow, the ozone concentration significantly decreased to 20 μg m^{-3}, nitrogen oxides are below the detection limit due to the fact that smoke can completely absorb NO_x [46], ozone sink in such conditions mainly occurs on aerosol particles [47]. We also selected aerosol samples along the route using a high-volume sampler for filters, and then carried out a chemical analysis for the ionic composition. It was found that under the influence of nearby fires, the concentration of sulfate ions increases to 4.7 μg m^{-3} against 0.14 μg m^{-3}, the concentration of potassium ions up to 0.32 μg m^{-3} against 0.069 μg m^{-3}.

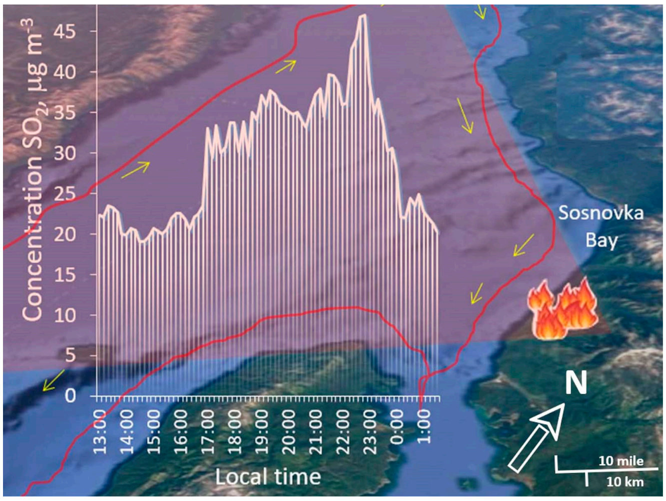


Figure 8. Temporal variation of SO_2 near Sosnovka Bay (29 July 2019).

Under the conditions of smoke exposure during the passage of the vessel along the eastern coast of Middle Baikal, an additional anthropogenic influence of enterprises and the residential sector of the settlement of Ust-Barguzin on the general pollution of the Baikal atmosphere was observed. So, when the ship approached the Svyatoi Nos Peninsula, a significant increase in ozone concentration was observed up to 73 µg m^{-3}, sulfur dioxide concentration up to 15 µg m^{-3}, nitrogen dioxide up to 5–7 µg m^{-3} with a sharp change in the wind direction to the south from a large settlement Ust-Barguzin due to the screening effect of the mountain range of the Svyatoi Nos Peninsula. Anthropogenic emissions from the territories where large settlements and industrial facilities are located have a significant impact on the formation of the spatial and temporal distribution of gas impurities over the lake's water area.

When the research vessel enters the bay of Bezymyanka in the Middle Baikal, the influence of the coastal settlements of Goryachinsk and Turka begins to manifest itself noticeably. Upon arrival at the parking lot in Turka, an increase in sulfur dioxide concentration is observed from background values of 4–5 µg m^{-3} to 30 µg m^{-3} (Figure 9a). An increase in SO_2 concentration was found at the mouths of the river Selenga near the village Kharauz, where a stable high level of sulfur dioxide is observed even at night, right up to the ship's exit from this area (Figure 9b).

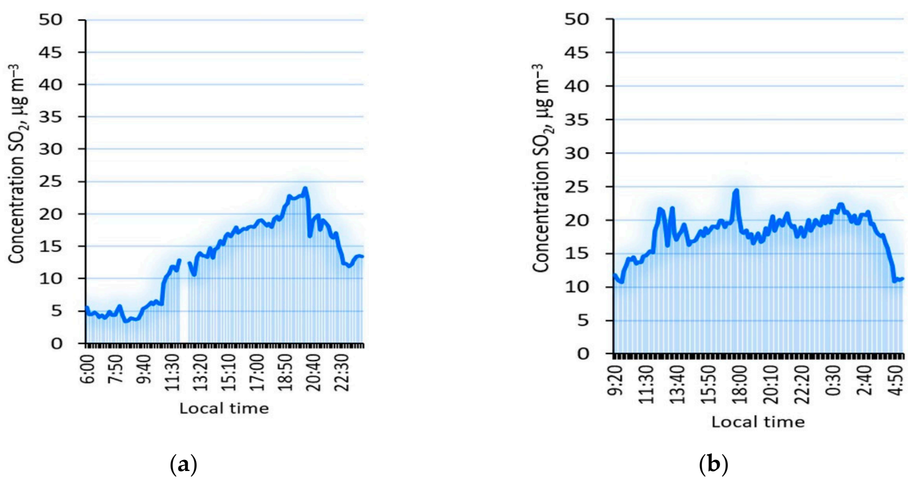


Figure 9. Temporal variation of sulfur dioxide concentration over the water area of Lake Baikal near settlements: (**a**) Turka (31 July 2019); (**b**) Kharauz (1–2 August 2019).

When the vessel moves near the coastal zone of the southeastern coast of Lake Baikal, the influence of settlements is clearly visible (Figure 10). This figure shows the largest settlements on the southeastern coast of Lake Baikal. The lowest concentrations are observed, as a rule, far from settlements, but nevertheless, under the conditions of the night breeze, the influence of anthropogenic outflows is noticeably manifested in the water area of Lake Baikal at a distance of 7–8 km from the coastal settlements of Tankhoy and Vidrino. This confirms that anthropogenic emissions from the territories where large settlements are located. Industrial facilities have a significant impact on the formation of the spatial and temporal distribution of gas impurities in the Lake's water area.

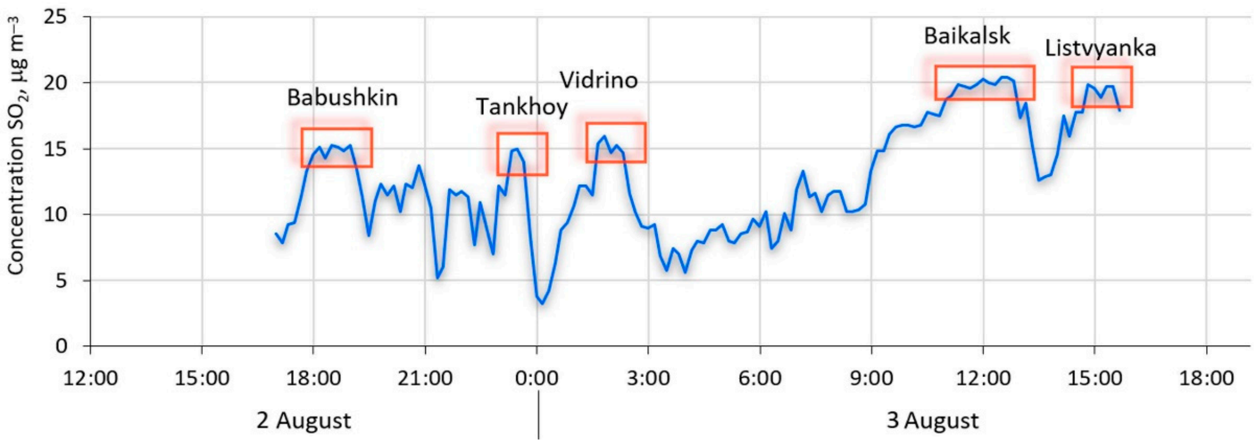


Figure 10. Temporal variation of sulfur dioxide concentration over the water area of Lake Baikal along the southeastern coast in the period 2–3 August 2019.

4. Conclusions

Complex experimental studies of spatial–temporal variability of small gas impurities (in the near-surface layer over the lake, using research vessel "Academik V.A. Koptyug", were performed from 24 July to 4 August 2019, in order to analyze and estimate the pollution of the atmosphere over Baikal in the firehazardous summer period with the purpose of creating the physical models of formation and transport of trace gas admixtures and aerosol fields of the atmosphere, taking into account the specific physical-geographic features of the Baikal region.

From the results of on-ship observations of air pollutants, we found significant differences in the composition and nature of the variability of gas and aerosol components in the atmospheric air than in the continental regions near Lake Baikal. Anthropogenic emission from the territories where large settlements and industrial facilities are located have a more significant impact on the formation of the spatial and temporal distribution of gas impurities over the Lake Baikal. One of the major sources of sulfur dioxide emissions is the Selenginsky pulp and cardboard mill. We suggest that the absence of nitrogen dioxide and high concentrations of SO_2 may mean that, possibly, the detected plume of SO_2 pollution near the southwestern coast accumulated for a rather long time (up to several hours), and gaseous nitrogen oxides had time to oxidize to nitrates. Over the water area of Lake Baikal, the content of nitrogen dioxide is significantly lower than that of sulfur dioxide. A comparative analysis of the results of measurements of trace gases SO_2, NO_2 over the Lake's water area and at the coastal station showed that during long-distance transport of anthropogenic impurities, gaseous nitrogen oxides are usually transformed into nitrates due to a higher oxidation rate of NO_2 than SO_2. At coastal stations (Boyarsk station, Listvyanka station) NO_2 concentrations, as a rule, increase synchronously with SO_2 concentrations.

High concentrations of ground-level ozone were noted up to 120 μg m^{-3} under the conditions of the formation of a stable air mass in the warm sector of the cyclone.

With the MODIS satellite observations, the HYSPLIT model and on-ship observations, we established that the spatial–temporal variability of gas impurities over the water area of Lake Baikal is largely formed under the influence of transport from anthropogenic sources, including flue gases from forest fires, that is, it depends on the geographical distribution of their sources and the prevailing circulation of air masses in a particular area. Despite the spatial heterogeneity of the SO_2 field distribution over the water area of Lake Baikal, in general, a stable daily variation of SO_2 is observed with a maximum in the daytime and a minimum in the morning hours.

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