2. Atmospheric and Marine Geochemical Characteristics of the White Sea

In-depth descriptions of the atmospheric and marine geochemical characteristics of the White Sea can be found in the work by Berger et al. (2001). The following information is only a brief introduction.

The White Sea is an almost landlocked extension of the Arctic Ocean indenting the shores of northwestern European Russia. The northern boundary of the sea runs along a line joining Cape Svyatoy Nos and Cape Kanin Nos (Figure 1). The area of the White Sea is 89,600 km^2; the volume is 5,400 km^3; the average depth is 60 m; and the maximum depth is 343 m (Babkov, Golikov, 1984).

The White Sea is traditionally divided into seven parts, as shown in Figure 1. The northern part of the White Sea, the Voronka, provides an opening to the Barents Sea and forms an external part of the White Sea. Within the Voronka is the Mezen Bay. Three other bays represent the interior part of the White Sea: Kandalaksha Bay, Onega Bay, and Dvina Bay. Into these bays empty the Mezen, the Northern Dvina, and the Onega Rivers. The White Sea is connected to the more northerly Barents Sea by a long, narrow, and shallow strait named Gorlo (throat). The Basin is where most of the deep water is found. The coastline is heterogeneous and complex. The shores of Kandalaksha Bay are heavily dissected with numerous inlets and fjords. Most islands of the White Sea are located in Kandalaksha Bay and Onega Bay. The western coast is hilly while the eastern coast is primarily lowland. The western shores of the Sea are formed by exposed ledge rock, while clayish and sandy beaches predominate on the eastern coast.

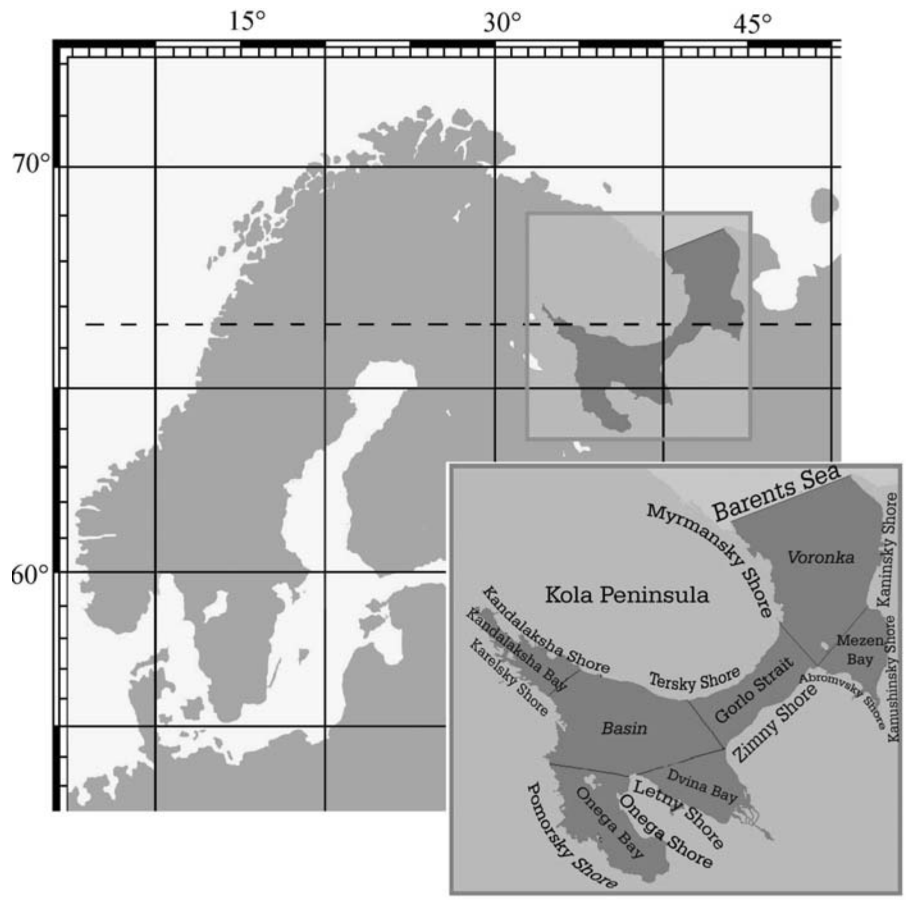

Figure 1. Map of the White Sea and its regions (Berger et al., 2001).

2.1 Meteorology

Characteristics of atmospheric pressure patterns over the North Atlantic and the Arctic Ocean basins determine the monsoon character of alternating winds dominating the White Sea. This causes northeast winds to prevail in the summer and southwest winds in winter. In summer, when the anticyclone over the Barents Sea interacts with the cyclone in the south of the White Sea, winds arise in the northeast quarter of the horizon accompanied by low cloudiness and rain. In the winter, low-and high-pressure areas are reversed: the anticyclone moves to the south of the White Sea, whereas the cyclone shifts to the Barents Sea. This meteorological pattern results in winds from the southwest. The sky becomes clear, and air temperatures decrease. In winter, the Atlantic cyclone often shifts south passing over the White Sea and southwest winds arise, cloudiness increases, temperatures rise, and snow falls. In winter, northeast winds coming from the Kara Sea and northwestern Siberia result in clear skies but temperatures dipping as low as -20 to -30^{o} C. In the summer, temperatures can reach +30° C; however, temperatures average about 15-20° C. In the northern part of the White Sea, the temperature is usually lower than that found in the southern part.

2.2 Geology

The topography of the White Sea floor is diverse with a variety of depths (Figure 2). In the Voronka maximum depths are 60-70 m with multiple-oriented northwest underwater ridges of heights from 8-12 m to 35-45 m, on average. A fairly deep trough approaches the Tersky Shore and connects the Voronka to the Gorlo Strait. A shallow zone lies along the Kanin Peninsula Shore and gradually converts into a gentle slope. In the Gorlo Strait, troughs and ridges stretch parallel to the Tersky and Zimny shores alternating with separate rises and local troughs averaging 40 m in depth, and individual troughs extending down to 100 m below the surface. The topography of Dvina Bay floor is relatively homogenous. A number of banks stretch along the southern and southeastern parts of the bay. Maximum depths over 100 m are found in the northern part of the Sea, such as in Cape Tury, which has a depth of 343 m.

The deepest, central part of the White Sea is referred to as the Basin. The floor topography of the Central Trough has local rises, mostly on its periphery. Due to its floor topography, Kandalaksha Bay is closely related to the Basin. In the northwest direction, depth sharply decreases to 50-100 m; the highest underwater ridge is in the head of the Bay. Onega Bay is a large depression elongated in the northwest direction. The central, deepest part of the Bay (50-60 m) is separated from the shallow, northwestern part (15-20 m) by a gently sloping ledge. In the southeast, an elevated region with a depth of 30-40 m adjoins the deepest part of the Bay. The head of the Bay is 10-20 m below the surface. White Sea tides are regular and semidiurnal in the Gorlo Strait and near the Tersky Shore, but they are shallow and semidiurnal in other parts of the Sea. A tidal wave originating in the Barents Sea and approaching the Voronka and the Gorlo Strait can produce 8- to 9-m high tides in Mezen Bay. In the other bays and in the Basin, the tidal amplitude is normally about 2 m, and the tidal current speed is rather high: 5 knots in the Gorlo Strait and 2 knots in Onega Bay.

The sediments on the floor of the White Sea differ in mechanical composition. A high content of sandy fractions (about 70%) is characteristic of the northern shoal of the Sea and the

Gorlo Strait. Near Cape Kanin Nos, sandy fractions decrease by 10-30% due to sediment enrichment with aleurite components. Certain regions of the Voronka, Mezen Bay, and Gorlo Strait contain 30-50% pebble and gravel components. Near the Tersky Shore, sand contains large amounts of bivalve and barnacle shells. In the White Sea Basin area, a narrow strip of sediments containing about 70% sand fraction runs along the coast; local sandstone cliffs occur. As the water depth increases, sediments contain more fine-grained material. In the deepest parts of the Basin and Dvina Bay, floor sediments consist of 70-90% pelitic components. Due to intensive water flow, sand occurs in shallow areas. In Kandalaksha Bay, pelitic sediments lie at the deepest levels. At depths to 100 meters, sand and aleurite predominate. In Onega Bay, sand and sand aleurite cover large floor areas.

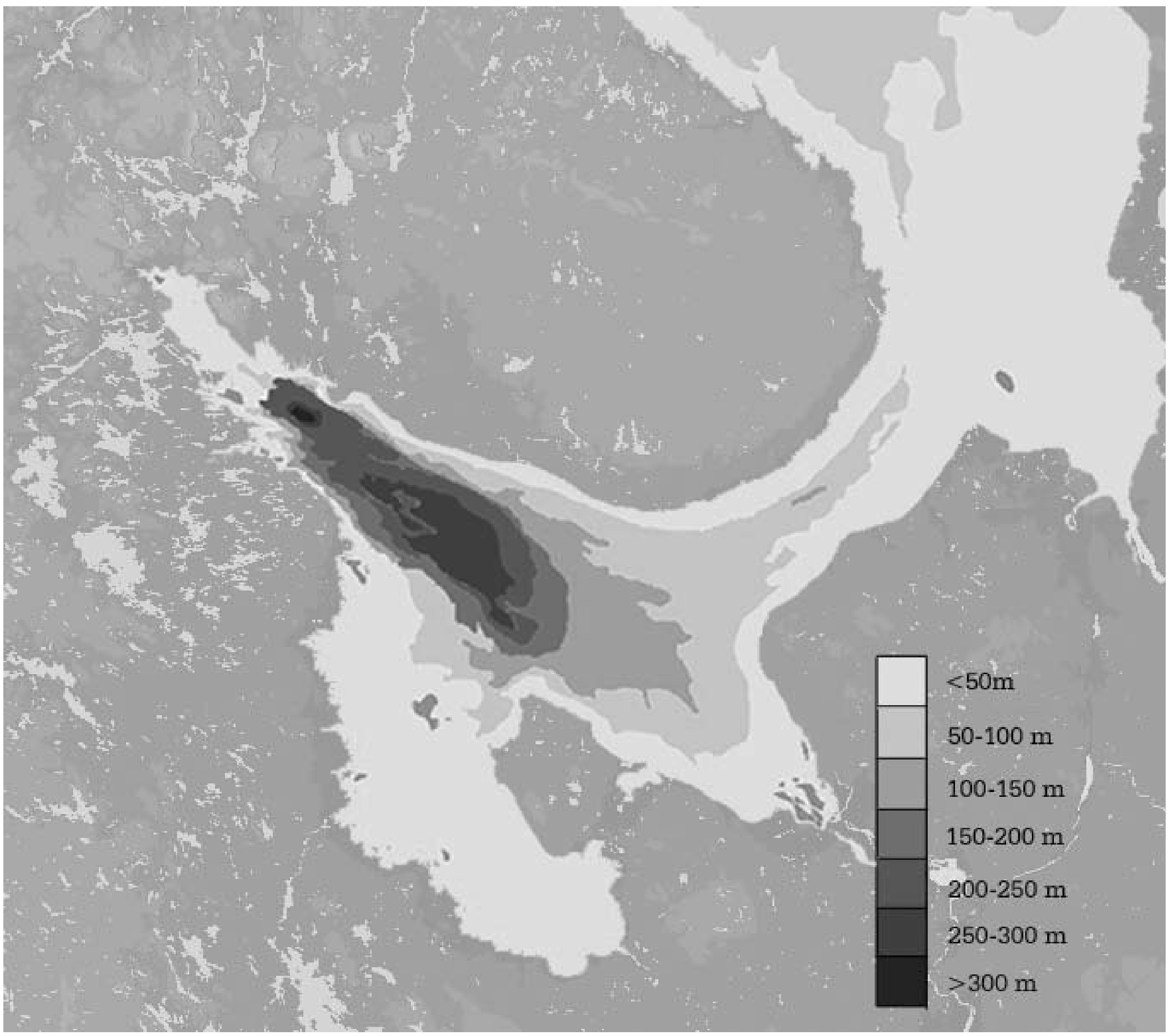

Figure 2. Map showing the bathymetry of the White Sea (modified from Berger et al., 2001).

2.3 Physical Oceanography

According to Berger et al. (2001), the White Sea exhibits interesting oceanographic characteristics. In the northern part of the Sea, summer water temperatures are low, about 6-8°C on average. In some areas, tidal currents cause an intense turbulence, which results in a well-mixed water column so that the water temperatures at the surface and on the floor are virtually the same. For example, vertical temperature homogeneity is typical of the Gorlo Strait region. A similar situation takes place in Onega Bay. Average summer water temperatures are higher, ranging from 9-12° C but can be as high as 14-16° C. In the Basin and internal bays, water surface temperatures are usually 13-15° C increasing to 20-24° C in the heads of the bays and in the shoal. In the inlets and creeks, in summer, water surface temperatures are generally higher than near open shores. Due to the intensive water circulation, summer heating reaches down to a depth of 15 m. Below this level, the water temperature sharply decreases, falling below zero at about 50-60 meters below the surface. The lowest constant summer temperatures of about -1.4° C to -1.5° C are registered in deep-water hollows of the White Sea. In winter, the water surface temperatures are close to the freezing point. These temperatures range from -1.2° C to -1.7° C in the Basin, Gorlo Strait, and Voronka, but vary from -0.5° C to -1.4°C in the bays. By the end of spring, usually in May, water starts warming. In autumn, water temperatures in the open sea vary but only minimally. In October, the temperatures of coastal waters rapidly decrease to low values as compared to the open sea.

In the White Sea, due to a large river discharge of fresh water and limited water exchange with the Barents Sea, salinity values are considerably lower than in the Arctic Ocean. Surface water salinity varies from 24-27‰ in the Basin and open parts of the bays and reaches about 29.5-30‰ in deep-water regions. At the heads of the bays, the average annual water salinity is 13-17‰. In the estuaries of large rivers, salinity decreases to less than 5-8‰. In the Gorlo Strait, salinity reaches 29‰ near the Tersky Shore and 24‰ at the Zimny Shore. Northward, near the Barents Sea boundary, salinity increases up to 32‰. In the White Sea, the dynamics of freshwater inflow causes sharp, seasonal variations in surface water salinity. In winter, when ice covers the surface of the White Sea, salinity increases (see CD-ROM, Environment/Salinity/Annual Cycle). In April-May, due to snow and ice melt, salinity drastically decreases to a depth of 2 or 3 m. Occasionally, in a surface layer of about 0.5 m thickness, the water becomes almost fresh in this period.

River discharge brings fresh water to the White Sea, which accounts for 95% of its water budget. Seasonal variations in water exchange between the Barents and White Seas depend on river discharge. About half the annual fresh water flows into the White Sea in the spring, intensifying water exchange between the Seas. The annual river water outflow from the White Sea is about 240 km^3. The annual river discharge into the White Sea is equivalent to a 2.6-m thick layer of water; precipitation and evaporation are equal to a 37-cm and 24-cm layer; respectively. At the same time, the seasonal sea-level variations are within several centimeters.

2.4 Hydrochemistry

In the White Sea, high oxygen concentrations of 6.06 to 8.59 ml L^{-1} are observed. Surface waters are most aerated in Onega Bay and the Gorlo Strait. Even in the deepest water layers of Kandalaksha Bay, Dvina Bay, and in the Basin, oxygen concentrations of 6.6 to 7.8 ml L^{-1} are rather common. Waters from the Barents Sea that are released into the White Sea (approximately 21.3 x 10^6 metric tons) contain a larger annual oxygen amount. However, during a year the White Sea gives back to the Barents Sea (approximately 21 - 22 x 10^6 metric tons), an equal oxygen amount is exchanged. Therefore, the oxygen balance of the White Sea depends on the processes occurring within the entire water layer. The total oxygen is obtained from the oxygen content of river waters and from photosynthesis. However, the available data is insufficient to calculate the oxygen balance of the White Sea. The seasonal dynamics of oxygen shows that, in surface waters, the concentration is highest in spring. During the summer-autumn period, oxygen concentration decreases due to a reduction in photosynthetic activity and an increase in remineralization of organic matter.

Inorganic nitrogen exists mostly in a maximally oxidized form, i.e., nitrates make up about 80% of all nitrogen-containing inorganic substances. In the White Sea, an average concentration of nitrate varies from 52 mg m^{-3} in surface waters up to 70 mg m^{-3} on the floor. In spring, the highest concentration of nitrates, 60 mg m^{-3}, is found in the euphotic layer of Onega Bay, while the lowest concentrations are found in Kandalaksha Bay and in the Basin – 30 mg m^{-3} and 20 mg m^{-3}, respectively. In autumn, when total nitrate increases to 40-50 mg m^{-3}, the discrepancies among the regions grow. In Dvina Bay, nitrate is at a maximum – 50 mg m^{-3} – while in the euphotic layer of Kandalaksha Bay, Onega Bay, and the Gorlo Strait, the concentration of nitrate is only 35-40 mg m^{-3}. In the White Sea, nitrite makes up not more than 10% of the total inorganic nitrogen reservoir, so its contribution is insignificant to the nitrogen supply for phytoplankton. In the euphotic layer, the nitrite content is about 1.7 mg m^{-3}, increasing to 3.3 mg m^{-3} in autumn, with the maximum concentration observed in Mezen and Onega Bays. Ammonia reaches a maximum concentration of 20 mg m^{-3} in autumn after oxidation is completed, then in winter, its content falls to half or one-fourth of this value.

In the White Sea, phosphates are mostly presented as inorganic forms of phosphorus-containing compounds with an average of 20 mg m^{-3} and not more than 15 mg m^{-3} of phosphorus in the euphotic layer. In August, phosphorus content drops to 10 mg m^{-3} in the neritic zone and below the detection limit in the euphotic layer of the pelagic area. In October, these values are equal to 11-16 and 9 mg m^{-3}, respectively. Phosphates vary considerably in certain regions of the Sea. In summer, due to intensive turbulence the concentration of phosphates is much higher (11-14 mg m^{-3}) in Onega Bay than in surface waters of the Basin. In Onega Bay, the content of phosphates is actually the same at all depths as compared to other regions where it varies with depth reaching maximum values in the deepest parts of the Sea. Compared to the Basin and Kandalaksha Bay, where phosphates are usually low, in shallow freshened regions of Dvina, Onega, and Mezen Bays, during the period of active vegetation, phosphates average 5 mg m^{-3}, and phytoplankton, consequently, gets more nutrition.

In the White Sea, the content of silicate varies considerably from season to season. When there are extensive blooms of phytoplankton, silicate in the euphotic layer never falls below the detection limit. According to long-term observation data in Mezen and Dvina Bays, the content of silicic acid is never less than 500 and 400 mg m^{-3}, respectively. The maximum silicate content of 2000 mg m^{-3} and above was registered in Dvina Bay. In deeper waters, the silicate concentration is more or less consistent (450 mg m^{-3}) for the entire water basin. In spring and summer, silicic acid decreases due to dissolution in surface waters; then in autumn and winter, it increases. However, no major trends are revealed in annual variations of this hydrochemical characteristic.

2.5 Zooplankton

According to recent reports about the White Sea, zooplankton is divided into 142 taxa with the most diverse taxa being tintinnids and copepods (Pertzova and Prygunkova, 1995; Berger et al., 2001). In addition, in a water column, pelagic larvae and eggs of mollusks, echinoderms, polychaetes, and crustaceans occur temporarily.

Compared to the Barents Sea, White Sea plankton fauna is less diverse. Several zooplankton taxa typical of the Barents Sea, *Radiolaria*, planktonic *Foraminifera*, *Siphonophora,* and *Ostracoda*, do not inhabit the White Sea. Other taxa like *Copepoda* are represented by a significantly lower abundance of species. Several factors like strong tidal currents, intensive water mixing in the Gorlo Strait, and very low salinity make the composition of species in the White Sea comparatively poor. Neritic species comprise a major portion of White Sea zooplankton, Arctic species - 42%, arcto-boreal species - 41%, and boreal species - 17%.

In earlier studies, the White Sea was considered to have low organism abundance and zooplankton productivity (Zenkevich, 1947; Epstein, 1963). However, in the many regions of the White Sea, except for the Gorlo Strait (Troshkov, 1998) and Mezen Bay, zooplankton biomass has been found to be 200 mg m^{-3} on average, sometimes as high as 760 mg m^{-3} (Bondarenko, 1994) to 2,470 mg m^{-3} (Pertzova and Prygunkova, 1995), which compares well with the neighboring Barents Sea.

Based on the averaged data from different regions of the White Sea, we can roughly estimate the total wet weight of its zooplankton biomass at 0.65×10^6 tons (Berger et al., 1995). The volume of the White Sea is 5.4×10^3 km^3, which is 0.0004% of the world ocean's volume of $1{,}370\times10^6$ km^3 (Moiseyev, 1969). White Sea zooplankton biomass is 0.0032% of the total world ocean zooplankton biomass of $20\text{-}21.5\times10^9$ tons (Vinogradov, 1955; Bogorov et al., 1968). As seen, the average zooplankton biomass of the White Sea is more than eightfold of that of the world ocean**.**