Chapter I Dissertation Summary

1. Scientific background

The Arctic region is recognized as the fastest warming area in the world (IPCC 2014, 2022). The observed increase in air temperature, along with the enhanced inflow of warm waters, further accelerates the process of glacier melting. In coastal zones, melting glaciers significantly reduce water transparency by releasing vast amounts of mineral suspended matter, visible often as dark-brown plumes. High concentrations of suspended particles in the water column lead to significant light absorption, resulting in a reduced vertical range of the euphotic zone. The properties of particles and aggregates (marine snow), such as size, structure, and transparency, also change drastically along gradients caused by different glacier types. This crucial role of suspended particles makes the detailed characterization of the quantity and type of matter released into the water column due to glacier melting key to understanding the biogeochemical mechanisms that affect processes in the surrounding ecosystems. The particle size distribution (PSD) influences their sinking rates, which, in turn, affect the horizontal and vertical transport of suspensions in the water column, as well as the rate of sedimentation of glacial deposits in bays (Moskalik et al., 2018; Szczuciński, Zajączkowski & Scholten, 2009; Zajączkowski, 2008b).

Suspended particles in the marine environment consist of both organic and inorganic components. The organic fraction includes particulate organic matter (POM), which originates from living organisms such as phytoplankton, zooplankton, and detritus from decomposed biological material. The inorganic fraction, also known as particulate inorganic matter (PIM), mainly consists of mineral particles that may come from terrestrial runoff, coastal erosion, and glacier melt (Babin & Stramski, 2004; Moskalik et al., 2018). The changing concentration of various types of particles in seawater directly affects the optical properties of marine waters. However, apart from the variability in suspended particle concentrations, the type of particles present, their mineralogical composition, size distribution, shape, and color also significantly influence the optical properties of seawater (Mobley 2022). Particles significantly limit the penetration of light into the water column, thereby affecting the underwater light regime, which is essential for photosynthetic organisms (Overland et al., 2019; Urbański et al., 2017; Zajączkowski, 2008a). Reduced light availability caused by increased turbidity may limit the photosynthetic activity of phytoplankton, which forms the base of the food web, thus impacting the overall productivity and ecological dynamics of fjord ecosystems. Primary production (PP) provides the fundamental ecosystem service of supplying energy to the entire marine food chain and plays a crucial role in the global carbon cycle and the Earth's atmospheric oxygen supply. Understanding how changes in suspended particle concentration and composition affect primary production is essential for predicting the overall state of ecosystems in Arctic fjords.

Satellite remote sensing is a primary tool for obtaining information about environmental changes on a broad spatial scale and with high temporal resolution. However, the application of remote sensing algorithms in fjord ecosystems faces several challenges. Firstly, these waters contain large amounts of land-derived suspensions, where both organic (phytoplankton) and inorganic (mineral) particles, with varying absorption and scattering characteristics, as well as dissolved substances, affect the absorption properties (Pegau 2002; Sagan & Darecki 2018). Secondly, it is a dynamic environment where interactions between two types of water – marine and freshwater from melting glaciers – occur (Błaszczyk et al., 2009, 2013; Cottier et al., 2010). The full application of remote sensing in these areas is also limited by frequent cloud cover, the presence of sea ice or icebergs. Another issue with remote sensing observations is the frequent occurrence of chlorophyll a or primary production maxima in deeper layers of the euphotic zone, below the depth that can be effectively monitored by remote sensing methods. These challenges highlight the complexity and limitations inherent in remote sensing of fjord areas, particularly those influenced by glaciers. The solution lies in combining in situ observations with satellite data. Many studies aimed at determining suspended matter concentration have utilized such a combination of methods (Chu et al., 2009; Doxaran et al., 2002; Schild et al., 2017). However, only the integration of additional information, such as meteorological data (Hock 2003; Bartholomew et al., 2010; Chu et al., 2012; Schild & Hamilton 2013, Schild et al., 2017), allows for long-term modeling of these processes and reveals general trends in melt processes and suspended matter inflow. Despite the aforementioned limitations, remote sensing remains an important tool for studying suspended particles in Arctic fjords, offering insight into the processes of glacial meltwater runoff. The integration of satellite data with in situ measurements, meteorological data, and advanced modeling techniques enhances our ability to monitor and predict changes in suspended matter concentrations and their ecological consequences (Comiso & Hall, 2014; Konik et al., 2020, 2021; Urbański et al., 2017).

2. Scientific objectives

The primary aim of this study was to investigate the characteristics of particles released into fjords by melting glaciers, determine their impact on primary production processes, and verify the hypothesis of a progressive decline in water transparency in Kongsfjord due to increased concentration of suspended matter released from glaciers, commonly referred to in the literature as "water darkening" (Aksnes et al. 2009; Konik et al. 2021). Methodologically, this work developed and applied an approach to combining in situ measurements, satellite observations, and meteorological data to remotely determine suspended matter concentrations in the fjords of Spitsbergen and assess these changes over a long-term period. Simultaneously, the use of machine learning techniques in this study opened the possibility of utilizing all available high-resolution satellite data to more accurately characterize the spatial and temporal variability of suspended matter concentrations.

In this dissertation, three main objectives were identified and achieved:

3. To describe the spatial variability of suspended particles in the fjords of Spitsbergen by characterizing the mineral composition, suspended particular matter concentrations, the proportion of organic to mineral matter, and the particle size distribution in the immediate vicinity of the source of the suspended matter, which are the individual glaciers terminating both at sea and on land.
4. To determine the influence of glacial meltwaters on the amount of organic matter produced during the summer season and assess its impact on the observed spatial changes in primary production processes in the fjords of Spitsbergen, both at the surface and within the water column.
5. To develop an algorithm for remotely monitoring suspended particle concentrations in the fjords of Spitsbergen and modeling the average particle concentration for each day of the summer season to assess the water darkening process over a long-term timescale.

3. Results

The Arctic region is undergoing significant environmental changes caused by climate change, which have a profound impact on glaciers and, consequently, on marine ecosystems. One of the effects of these changes is the increased inflow of suspended particles caused by the accelerating melting of glaciers. This summary synthesizes the results of three research articles dedicated to this issue, which constitute the present doctoral dissertation.

Publication No. 1

Dragańska-Deja, K. 2024. "Characterization of Suspended Particles at Different Glacial Bays at Spitsbergen." Oceanologia 66(2):239–49. doi: https://doi.org/10.1016/j.oceano.2023.12.001.

The aim of the first article was to characterize suspended particles in the coastal waters of glacial bays in the fjords of Spitsbergen's western coast. Using a laser particle size analyzer (LISST 100X) and X-ray techniques (XRD), the particle size distribution (PSD) and detailed mineral composition of suspensions in different glacial bays were determined, as well as the spatial variability of concentration of suspended matter. Eight glacial bays in Hornsund and four in Kongsfjorden were studied, allowing for a comprehensive comparison of suspended matter released by melting glaciers. The results were compared with geological data on the bedrock found near the studied glaciers.

The results of the study show that the concentration of organic matter (POM) is significantly lower near the glacier cliffs compared to inorganic matter (PIM), which accounts for 82.5% to 97.9%. A noticeable decrease in SPM concentration was observed in the surface water layer away from the meltwater source. In the context of climate change, special attention should be paid to carbonate minerals in the suspension. $CaCO_3$, a highly mobile chemical compound, can play a significant role in the greenhouse gas CO_2 cycle. In Gashamna Bay and near Korberbreen and Samarinvagen, XRD analysis showed high carbonate mineral content, attributed to the erosion of Early Ordovician carbonate rocks by glaciers. Although carbonate rocks are also found near Paierlbreen, mineralogical analysis showed only 8% calcite by weight and less than 2% dolomite. The mineral composition of the studied glacial bays varies significantly due to differences in glacial bedrock geology, age, and erosion rates. The study observed that the median particle size characteristics in different glacial bays vary depending on the dominance of different mineral compositions. This points to differences in glacial sediments in terms of particle settling, aggregation, and composition.

This study provides valuable insights into the variability of particle sizes and the dominance of mineral particles from melting glaciers. These results are crucial for improving the accuracy of optical models used in remote sensing and for predicting the ecological impacts of increased suspended matter concentrations. The supply of nutrients from melting glaciers also affects primary productivity.

Publication No. 2

Dragańska-Deja, K., Stoń-Egiert, J., Wiktor, J., and Ostrowska, M. 2024. "Productivity of Spitsbergen Fjords Ecosystems in Summer Spatial Changes of in Situ Primary Production in Kongsfjorden and Hornsund in the Period 1994-2019." *Ecology and Evolution* 14

This article investigates the impact of glacial meltwaters on primary productivity in Arctic fjords. It examines the spatial variability of primary production in three different regions of the fjords: near the glaciers, in the inner parts, and in the outer zones of Spitsbergen's Arctic fjords: Hornsund and Kongsfjord. Unique, long-term in situ data allowed for a comprehensive description of summer primary production variability in the fjord region and its dependence on spatial environmental changes. The surface primary production value at 0 m depth (Pe (0)) in both studied fjords was higher in areas influenced by glacial waters, decreasing towards the outer parts of the fjords. In Kongsfjorden, a gradual decrease in the mean Pe(0) value was observed, from 2.18 ± 2.75 mgC m^{-3} h^{-1} near the glaciers to 1.53 ± 1.28 mgC m^{-3} h^{-1} in the outer fjord. In Hornsund, this decline ranged from 6 ± 5.39 to 1.77 ± 0.51 mgC mgC m^{-3} h^{-1}, highlighting a clear gradient in primary production (PP) from the glacier to the outer fjord zones.

Although nutrient content may be highest near glaciers, due to the erosion of bedrock by moving glaciers and the release of large amounts of inorganic suspensions with varying mineral compositions, light availability is limited to the surface layer. The spatial distribution analysis of integrated primary production in the water column (Pi) indicates that glacier-proximal areas of the fjords are characterized by the lowest productivity. At the fjord mouths, the mineral particle content is lower, increasing light availability, but nutrient scarcity is observed in open waters during summer. The highest average Pi values in Kongsfjorden were recorded in the outer zone (769.12 ± 540.53 mgC m^{-2} day^{-1}), while in Hornsund, the highest values were noted in the inner zone (1203.02 ± 604.34 mgC m^{-2} day^{-1}).

The study emphasizes the complex interactions between environmental factors—particularly suspended mineral particle concentration—and primary production in Arctic marine ecosystems. This research also highlighted the need for in situ measurements to validate and calibrate satellite algorithms, particularly in regions experiencing dynamic environmental changes, such as Spitsbergen's fjords. Continued monitoring and analysis, combining satellite and in situ data, will be crucial for deepening our understanding of the complex mechanisms regulating primary production and the overall state of ecosystems in polar fjords.

Publication No. 3

Submitted to *Polish Polar Research*

Dragańska-Deja, K., Urbański, J. "Quantifying Darkening of Svalbard Fjord Using Landsat/Sentinel-2 Images and In-situ Measurements."

The third article focuses on quantifying the phenomenon of decreasing water transparency ("water darkening") in Kongsfjorden using long-term data from Landsat and Sentinel-2 satellites, in situ measurements, and meteorological data. The study established an empirical relationship between remote reflectance values in three channels (blue, red, and infrared) and measured in situ values of suspended particle concentrations. The use of two visible light channels was significant due to the varied color of suspended particles resulting from different mineral compositions in the individual glacial bays, as demonstrated in the first article.

A method was developed for masking fjord areas covered by various forms of icebergs using classification techniques employing machine learning. The analysis of suspended particle concentration (SPM) changes during the periods 1985–2000 and 2015–2020 showed a significant increase in SPM, indicating a progressive darkening of the fjord waters. This darkening is linked to climate change, as rising temperatures result in increasing amounts of suspended matter carried by meltwater from glaciers into the fjord.

Average SPM values were determined in a 6 km zone from the glacier fronts. Using regression methods, the relationship between average SPM values and the 6-day sum of all positive mean daily temperatures above zero degrees Celsius (Positive Degree Days - PDD) was determined. This allowed for the modeling of average SPM values for each day in July and August over a 35-year period. Comparing these SPM concentration values revealed the presence of a water darkening process. The average SPM in the zone covering over half of the fjord increased by 36% between 2015-2020 compared to 1985-2000, significantly reducing water transparency. The decrease in transparency has important ecological implications, affecting primary production and interspecies interactions in the fjord. The use of advanced machine learning techniques increased and improved spatial and temporal information, providing key data for future ecological models and remote sensing applications.

In summary, the research presented in the articles comprising this doctoral dissertation provides a comprehensive view of the impact of suspended matter from glacier melt on Arctic marine ecosystems. Increased meltwater discharges lead to higher concentrations of suspended matter with diverse mineral compositions, reduced water transparency, and significant changes in primary productivity. The integration of satellite data, in situ measurements, and advanced analytical techniques allows for precise monitoring of these processes and their ecological consequences, which is crucial for understanding and predicting the dynamics of changes occurring in Arctic marine ecosystems.

4. Conclusions and Scientific Achievements of the Doctoral Dissertation

The main focus of this dissertation was the analysis of the characteristics of suspended particles in the fjord waters of Spitsbergen, their role in shaping the spatial variability of primary production processes, and the development of innovative methods for the remote assessment of suspended particle concentration variability and the water darkening process in fjords. This research introduces new perspectives in understanding the environmental dynamics of the western Spitsbergen fjords and represents an innovative approach in this field of science, addressing a significant gap in existing knowledge.

The primary tasks accomplished in this doctoral dissertation are as follows:

- Describing the mineral composition of suspensions originating from glaciers with different bedrock types, based on in-situ data and linking this information with geological data from the studied area.
- Determining the variability in the particle size distribution (PSD) of suspended particles in different glacial bays depending on the mineral composition of the suspensions.
- Assessing the variability of suspended particle concentrations and the ratio of mineral suspensions to organic matter.
- Establishing the spatial and temporal variability of primary production based on long-term in-situ data and determining the influence of distance from the glacier on the primary production process.
- Confirming the importance of in-situ measurements for calibrating and validating remote monitoring algorithms, particularly in dynamically changing regions such as the fjords of Spitsbergen.

- Developing an algorithm using machine learning techniques for the quantitative analysis of the water darkening phenomenon in fjords and the spatial and temporal assessment of suspended matter concentrations.
- Identifying pathways and possibilities for utilizing the obtained results in modeling processes related to suspended matter using satellite remote sensing in the context of contemporary research on Arctic regions.

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