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Review Report on the thesis in fulfilment of the requirements for the degree of Doctor of Philosophy, Institute of Geophysics, Polish Academy of Sciences

Author: Kornelia Anna Wójcik-Długoborska

Title: "Variability of physico-chemical parameters of suspension transported from marine-terminating glaciers and their influence on the spectral properties of surface waters in glacial coves"

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The presented review report is organized in the following sections: project background, general description of the thesis, specific comments followed by a final evaluation statement.

Project background

Ongoing warming of climate has the greatest impacts in the polar regions where among many environmental changes it increases glacier surface melting leading to a major contribution to rapid sea-level rise. That increased mass losses from polar ice sheets and glaciers have emphasized also the need for observations of meltwater exiting glaciers. It is widely accepted that marine-terminating glaciers discharge mass through iceberg calving, submarine melting, and meltwater run-off. Iceberg production through calving can be quantified by in situ and remote-sensing observations, on the other hand, the meltwater run-off including the subglacial and submarine meltwater routes are not well understood and described. This is mainly due to the difficulties in observing the subglacial and proglacial environments at marine-terminating glaciers. However, there is one, indirect way to better understand the hydrology of the glaciers - the observations of sediment plums that exit glaciers. The presence of a sediment plumes is a strong marker for subglacial and inglacial meltwaters leaving the glaciers.

Understanding when, where and how much meltwaters leave the glacier is important for many reasons - firstly it may indicate how much sediments gets into the ocean, secondly it may provide insight into processes operating on the ice-bedrock interface and decide on the controls of glacier velocity. Number of studies, predominantly located in the Arctic (e.g. Greenland) showed that remote sensing can be used to map the occurrence and spatial distribution of sediment plumes.
confirming that Subsequent research showed that satellite imagery can be used to map the size and location of these sediment plumes. Despite this tremendous research effort there are areas that still require deepened study, particularly in the Antarctic. Candidate in her doctoral research decided to challenge one of the underexplored problems in the discipline the determination of the variability of turbid waters and concentration of suspended sediments from Antarctic glaciers.

Geographical focus of the thesis was one of the best studied areas of South Shetland Islands archipelago – the Admiralty Bay in southern part of King George Island, ca. 120 km from the Antarctic Peninsula. Quite unique setting offering access to diverse types of glaciers including Ecology Glacier entering coastal lagoon, Zalewski, Krak, Vieville – classic marine-terminating glaciers with high ice-cliffs and steep Ladies and Dera Icefalls. The candidate hypothesised that turbidity, which is one of the physico-chemical parameters of suspension transported from glaciers, is a sufficient indicator to identify the occurrence of sediment plumes. Candidate also assumed that in case of relatively small glacier bays the absence of high quality satellite data can be substituted by multispectral images from UAVs. In this ambitious thesis the Candidate defined four objectives:

1.) *To determine the variability of the physical and chemical parameters, including turbidity and suspended sediment concentration, of glacial suspensions transported from glaciers;*
2.) *To identify meltwater outflows on the basis of real and multispectral UAV images acquired;*
3.) *To conduct extended analyses of the shadow effect and the colour of the suspension from measurements of the spectral properties of suspensions transported from glaciers;*
4.) *To determine the suitability of existing algorithms for retrieving the turbidity of the surface water layer in glacial coves on the basis of satellite and UAV imagery, and finally to propose an algorithm calibrated to Admiralty Bay area glaciers.*

Thus, this thesis addresses the highly relevant and vital areas of current Antarctic glaciological and hydrological research.

General description of the thesis

The submitted thesis presents investigations of the variability of physico-chemical parameters of suspension transported from marine-terminating glaciers and their influence on the spectral properties of surface waters in glacial coves, Admiralty Bay, King George Island, South Shetland Islands.

The dissertation comprises 141 pages and does follow the standard structure of a PhD thesis in natural and physical sciences based on the collection of academic papers (3 papers and 1 technical note).
Thesis begins with extended abstract of the thesis presented in Polish and English. This part is providing a background for understanding the rest of the thesis. Candidate firstly presented the study motivation and overarching research objectives. Next, brief introduction to thesis outline explains the structure and order of papers selected for the collection. Then, the Candidate presents the key results from each to the manuscript:

a) investigations of turbid glacial meltwater using a high-resolution multispectral sensor mounted on an UAV
b) investigations of the influence of the shadow effect on the spectral characteristics of glacial meltwater
c) investigations of the influence of the colour of glacial suspension on the relationship between its properties and the spectral reflectance of marine waters
d) the presentation of a universal algorithm determining water turbidity to a set of satellite and UAV data from the Antarctic region

After the presentation of results main outcomes of the thesis are presented followed by the key references and author contribution statements.
The language is comprehensive and coherent at least for readers for whom English is not their mother tongue. The Polish version is identical to the English version and can clearly familiarise the native reader with the aims and main results and conclusions of the dissertation.
The thesis figures in the extended abstract are prepared in good editing and design standard.

However, what is missed in the introduction of the thesis is a conceptual figure presenting key components of the studied glacial environment - ideally with a cross-section through the glacier showing different routes of meltwaters escape. Such a figure may be presented during the oral defence – and used to explain the key terms.

Specific comments

Part 5.1. Investigation of turbid glacial meltwater using a high-resolution multispectral sensor mounted on an unoccupied aerial vehicle

Candidate stated that during the investigation it was possible to observe various shapes of sediment plumes forming in Suszczewski Cove, Herve Cove, Lussich Cove and in front of Zalewski Glacier. *What I missed in both the technical note published in Water and the extended summary was an attempt to classify these shapes. I wonder if there was any pattern detected in shape variability related to the state of the sea, tidal cycle or part of the season (temperature, precipitation). I kindly ask the Candidate to discuss the issue of shape variability (differences/ similarities) among studied glaciers during the oral defence.*
My second question is related to glaciomarine processes that occur at the ice-sea interface. I'm curious if during the remote sensing (UAV) investigations it was possible to capture the event of glacier calving or iceberg rolling event into the part of the bay with a developing sediment plume? Can calving or collapse of an iceberg change the shape of plume, may cause some type of dismemberment, or those processes are completely irrelevant processes for the turbidity of the waters in the fjord?

5.2. Influence of the shadow effect on the spectral characteristics of glacial meltwater
Second part of the thesis was concentrated on the potential effect of shadow formed by glacier fronts and relief on the surface of glacial bay, on the quality of remote sensing data. This case study proofed that shadows significantly affect the spectral properties of meltwater, reducing the amount of reflected radiation and proposed the methodological steps to reduce the shadow effect on analysis quality in remote sensing. This is a huge achievement of the doctoral research and provides a strong fundament for further studies.
As a field research practitioner, however, I wanted to find out what weather conditions are optimal to reduce the shadow effect, whether flying on a cloudy day is optimal solution? Or the high cloud cover in Admiralty Bay is usually coincided with harsh weather conditions that exclude drone flights?

5.3. The influence of the color of glacial suspension on the relationship between its properties and the spectral reflectance of marine water

In my opinion part 5.3 of the thesis is the major achievement of the doctoral research carried out by the Candidate. The research was based on probably most extensive application of UAV in South Shetland Islands in glaciological research. Candidate detected sources of sediments in catchment of Zalewski Glacier and found significant differences in their physical parameters including the colour differentiation – white and red sediment plumes). The study allowed to determine that the sediment delivered to the cove in front of the glacier comes from two geologically distinct source areas due to the presence of a tectonic fault under the

ice. I'm interested in Candidate opinion on the future of glaciomarine processes in front of Zalewski Glacier. *I wonder if the Candidate had a chance to observe any difference in retreat rates along the "white" and "red" parts of the glacier - suggesting that glacier movement on different bedrock implies different flow velocities? If that is the case, which part may retreat earlier? I would also like to hear if during the field observations or further remote sensing analyses the Candidate was able to detect periods when white sediment plumes dominated over red plumes and vice versa? Finally, I wonder which of two plumes is dissolved faster in water depths and in which part of the bay the mixing/merging of plumes is occurring?*

5.4. Adaptation of a universal algorithm determining water turbidity to a set of satellite and unoccupied aerial vehicles data from the Antarctic region

This part of the thesis aimed to design the Glacial Meltwater Turbidity Algorithm (GaMTA) calibrated and validated on data from heavily glaciated Antarctic areas. The new algorithm was tested and proved to be useful in processing both satellite and UAV imagery. However, the Candidate stated that improvement through validation and calibration on a larger dataset is needed. *I would like the Candidate to present the algorithm calibration/learning scheme that may improve the application and quality of algorithm. Is it possible to estimate the number of plumes to be tested for significant improvement of the accuracy of the algorithm.*

Final evaluation statement

The doctoral dissertation presented for review is a very valuable study of substantively planned and professionally executed scientific research carried out in difficult Antarctic conditions, which contributes valuable, original and solid knowledge to the field of glaciological-hydrological research in the polar regions. I really appreciate the candidate expertise in the field of remote sensing of Antarctic glaciomarine environments.

Considering the complexity of the research problem, the difficulty of conducting research on King George Island (Antarctic), the lockdown that paralysed not only the academy but also the normal functioning of the entire state during the period of this dissertation, and above all not giving up motherhood and struggling to make time for her daughter this **dissertation deserves a distinction.**

As I look at the great challenges the world faces in the future, including Poland, I am heartened to know that as brave, hard-working and ambitious female researchers as Mrs Wójcik-Długoborska will have an impact on the future of polar research that should allow us to build a better future that is in tune with the needs of the environment, including the deglaciating coasts of the world filled with turbid sediment plumes.

This thesis is ready to be defended orally and, in my opinion, meets the requirements laid down for the degree of Ph.D. by the Institute of Geophysics Polish Academy of Sciences examination guidelines.

In conclusion, the dissertation submitted to me for evaluation by Mrs Kornelia Anna Wójcik-Długoborska constitutes an original solution to the problem posed and meets the requirements for dissertations PhD thesis by "Law on Higher Education and Science". In view of this, I submit to the Scientific Council of the Discipline of earth science and environment of the Institute of Geophysics Polish Academy of Sciences to admit the Candidate to the further stages of the proceedings for the awarding of the degree of doctor in the field of sciences and natural sciences in the discipline of the earth science and environment.

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