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Review report

on the doctoral dissertation
submitted by Dhanushka Devendra, M.Sc.
to the Scientific Council of the Institute of Oceanology of the Polish Academy of Sciences

This is my review of the doctoral dissertation of Dhanushka Devendra, MSc, entitled *Late-glacial and Holocene Paleoceanographic Changes in the European Arctic Based on a Multiproxy Approach,* prepared under the supervision of Prof. Marek Zajączkowski and Dr Magdalena Łącka-Wojciechowska from the Institute of Oceanology of the Polish Academy of Sciences. The review was completed at the written request of Prof. Monika Kędra, Chair of the Scientific Council of the Institute of Oceanology of the Polish Academy of Sciences, received on September 30, 2024.

Structure and language of the dissertation

The thesis is written in English and consists of a series of two co-authored peer-reviewed papers published in 2022 and 2023, as well as a manuscript of the third contribution submitted to the journal *Climate of the Past* in 2024. The thesis is compiled in the form of a compact volume of the doctoral dissertation, containing abstracts, extensive summaries in English and Polish, and three publications. The thesis is accompanied by statements from all co-authors on their individual contributions. The dissertation is based on the following publications:

I. **Devendra, D.**, Łącka, M., Telesiński, M.M., Rasmussen, T.L., Sztybor, K., Zajączkowski, M. (2022). Paleoceanography of the Northwestern Greenland Sea and Return Atlantic Current Evolution, 35–4 kyr BP. ***Global and Planetary Change***, vol. 217, 103947, https://doi.org/10.1016/j.gloplacha.2022.103947;

II. **Devendra, D.**, Łącka, M., Szymańska, N., Szymczak-Żyła, M., Krajewska, M., Weiner, A.K.M., De Schepper, S., Simon, M.H., Zajączkowski, M. (2023). The development of ocean currents and the response of the cryosphere on the Southwest Svalbard shelf over the Holocene. ***Global and Planetary Change***, vol. 228, 104213, https://doi.org/10.1016/j.gloplacha.2023.104213;
DD: Conceptualization, Formal analysis, Investigations, Writing – original draft, Visualization

III. **Devendra, D.**, Szymańska, N., Łącka, M., Szymczak-Żyła, M., Krajewska, M., Telesiński, M.M., Zajączkowski, M. (2024 - submitted to ***Climate of the Past***). Postglacial environmental changes in the northwestern Barents Sea caused by meltwater outbursts. ***Clim. Past Discuss.*** [published preprint], https://doi.org/10.5194/cp-2024-52.

Assessing the structure and language of the dissertation, I do admit that the work is clear and well written. The terminology used in both English and Polish (summary) is correct. The terminology used is correct in both English and Polish (abstract). Tables and figures with location maps, multi-proxy charts, graphical models are carefully prepared and contain the necessary documentation to evaluate the results.

Assessment of the Candidate's individual contribution

The candidate has published his dissertation papers in co-authorship with 11 scientists affiliated with the Institute of Oceanology of the Polish Academy of Sciences, UiT-The Arctic University of Norway, NORCE–Norwegian Research Centre, and Akvaplan-niva AS (consulting company).

The candidate's contribution to **Paper #I** (Devendra et al., 2022) includes: counting the Ice Rafted Debris (IRD) fraction; co-authored construction of the age-depth model; co-writing the manuscript draft; and shared contribution to data interpretation, writing and editing of the final manuscript. His contribution to **Paper #II** (Devendra et al., 2023) includes: Conceptualization, Formal analysis, Investigations, Writing original draft, Visualization. His contribution to **Paper #III** comprises: collecting the sediment core; designing the research and experiments with the supervisor; constructing the age-depth model; shared efforts to perform the formal analysis; writing the original manuscript draft, and sharing data interpretation, writing, and editing of the final manuscript.

It is essential to stress that Dhanushka Devendra is the first author and the corresponding author in all three publications. By comparing the statements of all co-authors, I conclude that the PhD student has made a significant contribution to these publications and therefore his individual contribution to the completed dissertation is sufficient for further evaluation. It is evident that the research process required the comprehensive involvement of the entire research team. Without such collaboration, the research and preparation of the thesis would not have been possible.

Subject and objectives of the dissertation

The main objective of this study was to detect the spatial and temporal changes in bottom environmental conditions, sea surface conditions, and marine productivity variations in response to water mass changes, particularly the influx of Atlantic Water (AW) on the European Arctic. This northward transport of warmer Atlantic waters to the Arctic Ocean is the main player, controlling and regulating the European Arctic climate system and partly the climate in Europe itself. This PhD study is based on analyses of three marine gravity cores collected from the northeastern Greenland shelf, northwestern Barents Sea margin, and southwestern Svalbard shelf.

Recently that part of the Greenland shelf is influenced by the Return Atlantic Current (RAC), which transports warm Atlantic Water from the Fram Strait, as well as the East Greenland Current, which transports cold, sea ice-rich water from the Arctic. The other two study sites are controlled by warm and saline Atlantic Water, coming from the south. All three sites are highly suitable for studying the palaeodynamics of this sensitive system.

Nevertheless, it should be mentioned that the core from "the Greenland shelf" was retrieved at the slope 1170 m water depth that is much deeper than two other shallower cores retrieved at 133 m depth of the NW Barents Sea margin, and at 374 m depth of the SW Svalbard shelf. In consequence, we can assume that the paleodepths of these sites were comparable to the present depths or somehow shallower due to glacial conditions. It means that direct paleoenvironmental comparison of all three sites is limited due to their contrasting paleodepths.

The target stratigraphic interval was set from the late-glacial to the Holocene, representing the full transition between glacial and interglacial climatic and oceanographic conditions, as well

as the dynamic evolution of the present interglacial. It is a pity that all three cores do not record the same or similar time intervals, therefore, they cannot be well correlated. The Greenland slope core records the interval between 35 kyr and 4 kyr; the SW Svalbard shelf core covers the last 11 400 years, the NW Barents Sea core represents the last 14 700 years.

These aspects limit the integrated interpretation of the results due to the reduced spatial-temporal compatibility of the analyzed cores. Consequently, the three publications should be treated separately, which is also clearly visible in the text of the dissertation. However, what may integrate all the research results most is the focus on the influence of Atlantic waters on the studied system in this Arctic and subarctic region. In order to obtain the most comprehensive picture, an impressive range of different proxies has been used. This multi-proxy study employed a variety of sedimentological, micropaleontological, and geochemical proxies.

In general the thesis addresses more specific research objectives focused on: (1) paleoenvironmental dynamics controlled by the inflow of Atlantic Water (AW) and its impact on ice sheet stability during the late glacial and Holocene; (2) temporal and spatial distribution of meltwater pulses and their impact on environment; (3) responses of the European Arctic to abrupt climatic shifts (e.g. warm Bølling–Allerød vs cold Younger Dryas states); (4) Holocene variability of sea ice cover and ocean circulation; (5) Recent millennia trends in AW inflow and sea ice cover in the European Arctic.

Evaluation of thesis results

As mentioned above, my evaluation of the research results is done separately based on the three publications.

Paper #I. Devendra et al. (2022) document nearly continuous presence of Atlantic Water in the NW Greenland Sea during the last 35,000 years that highlights the persistent influence of these waters on the regional paleo/oceanographic conditions. This paper is a significant contribution because it reconstructs in detail the Return Atlantic Current evolution, providing insights into the long-term variability of AW inflow and its impact on the NE Greenland Ice Sheet stability. This study offers a more comprehensive understanding of the paleoceanographic conditions in the NW Greenland Sea compared to previous contributions that often focused on shorter time intervals and/or more specific paleoenvironmental events.

This research identifies two periods of Greenland Ice Sheet advances between 32-29 kyr and 26-23.5 kyr BP, which reduced meltwater influx to the NW Greenland Sea. During the Last Glacial Maximum, it shows that extensive sea ice cover was associated with the presence of subsurface Atlantic Water (AW). Authors stress the strong melting of glaciers and sea ice during the Bølling-Allerød period (approximately 14.6-12.7 kyr BP) due to the combined effect of warming and the flow of warm AW. Then the Younger Dryas Cooling (a. 12.8-11.7 kyr BP) was associated with the weakened Return Atlantic Current, reducing the advection of warm AW to the NW Greenland Sea. Approximately 11.7 kyr BP, the Return Atlantic Current reached its modern strength, with the maximum strength observed during the Holocene Thermal Maximum. Some aspects of the study replicate earlier findings, being in line with existing knowledge, such as the influence of AW on the NE Greenland Ice Sheet and the role of AW in regulating deep-water formation.

Paper #II. Devendra et al. (2023) explore the entire Holocene within 230 cm of Svalbard shelf sediments located on the NW Barents Sea margin. However, we have to be aware that this is

much shallower site than that one from the NE Greenland slope presented earlier (see Devendra et al., 2022). This study presents detailed reconstruction of the interplay between warm AW, Arctic water, and cold local water from the inner Hornsund on the dynamics of ice coverage. This multiproxy study provides a more comprehensive understanding of the regional developments and their effects on the local and regional climate and ocean during the Holocene. Results are compared to other studies conducted in the western Barents Sea.

The deepest record of this core is linked to the Preboreal Oscillation, indicated by proxies of cold Arctic water from the East Spitsbergen Current and thick sea ice cover dated between 11 and 10.2 kyr BP. The warmest conditions on the SW Svalbard shelf are interpreted between 10 and 7 kyr BP), with the increased Atlantic Water inflow, promoting sediment erosion and low sea ice cover. From 6.5 to 3.5 kyr BP, this region experienced cold surface temperatures and dynamic conditions due to icebergs and sea ice rafting, followed by warm Atlantic Water expansion with increased erosive activity and elevated temperatures between 2.3 and 1.5 kyr BP.

Paper #III. Devendra et al. (2024) present several new findings that further enhance our understanding of the paleoceanographic conditions in the northwestern Barents Sea over the last 14,700 years. The study identifies four distinct meltwater pulses between 14,700 and 8,200 cal years BP. These pulses are characterized by sudden drops in sea surface temperatures, increased sea ice formation, and increased terrigenous supply. This detailed identification and characterization of multiple meltwater pulses provide new insights into the deglacial processes in the region. The paper highlights the impact of the Storegga tsunami around 8,200 years BP on sediment redistribution in Kveithola. This finding is significant as it may provide clues to the far-reaching effects of the tsunami on the sedimentary environment of the northwestern Barents Sea. The research documents a period of strong coarsening of the northwestern Barents shelf after 3,500 years, which is attributed to a stronger inflow of Atlantic Water from the west. This observation adds to our understanding of the changes in ocean circulation and their impact on sediment dynamics in the region.

Assessment of the thesis

Positive aspects of the doctoral dissertation

1. A well-chosen study area that is extremely sensitive to paleo/oceanographic and paleo/climatic changes. However, the selection of core sites show some limitations.
2. An interesting and broader concept of the work, taking into account the multidimensional complexity of the depositional and paleoclimatic systems.
3. Well defined the time frame of all cores with the presented age-depth models.
4. The new findings of the dissertation contribute to more comprehensive understanding of the interactions between ocean circulation, meltwater pulses, and climatic changes during the last glacial, deglaciation and Holocene periods.
5. A significant part of the research methodology based on multiproxy approach is correct and valuable, however, some problematic issues are listed below.
6. This research provides excellent multiproxy data that may be used as reference data for future research on past and future climate dynamics. The most valuable are the data from

the NE Greenland slope core that are available from the PANGAEA Data Publisher for Earth & Environmental Science (Devendra et al. (2022): Paleoceanography of the NW Greenland Sea and Return Atlantic Current evolution, 35–4 kyr BP [dataset bundled publication]. PANGAEA, https://doi.org/10.1594/PANGAEA.943502).

7. The graphic correlation plots of all multiproxy data are well designed and clearly presented. I particularly appreciate the presentation of the foraminifera quantitative data in relative proportions and absolute abundances (#individuals per 1g dry sediment) dependent on sedimentation rates. This was made possible by applying the right methodology for sampling, preparation, sieving, picking and analysis. However, there are some methodological inconsequence's listed below.
8. Elegant presentation of simple graphical models of palaeoenvironments controlling the studied basins (fig. 7 in Devendra et al., 2022; fig. 8 in Devendra et al., 2023).
9. Achievement of the main objectives of the PhD project.
10. Extensive discussion of own results in relation to existing knowledge on the subject addressed.
11. Publication of the main part of the doctoral dissertation results in prestigious peer-reviewed international journals (2 out of 3 papers).

Some questionable aspects of the thesis

1. The choice of cores that shows some limitations restricting possibility of correlating them directly in time and habitat space. This study also lacks replicated cores testing local impacts on the core sedimentary records.
2. Partly lacking standardization of the research methodology in all three publications of the doctoral dissertation. For instance, Devendra et al. (2022) paper analyzed foraminifera from the >63 μm fraction, however, Devendra et al. (2023 and 2024) studied specimens from the >100 μm fraction.
3. The lack of graphic documentation of all or at least dominant species of foraminifera.
4. Missing access to the multiproxy datasets presented in two papers (i.e. Devendra et al., 2023, 2024)
5. Omission of multivariate statistics in all papers. I believe that this kind of statistics is essential for analyzing complex trends in multiproxy data.
6. Limited integration of the data results with the interpretations and the proposed models. Multivariate statistics would be of help to verify main trends in multiproxy data.

With regard to all of the above, I would like to address a few questions to the doctoral candidate:

A. What could we learn from comparison of benthic and planktic foraminiferal assemblages analyzed in all three cores? Please consider different depths and habitats.
B. Would you see any chance to identify the Storegga tsunami (~8.2 kyr BP) deposits within the core from the SW Svalbard shelf?

C. What coherent, i.e. unified research methodology would you adopt when starting similar research with the current experience gained while working on your doctorate project? Your answer could be a methodological added value that we all learn from your thesis.

D. Would you integrate all productivity proxies applied in your all studies? Would you see general trends and patterns in geochemical and micropaleontological proxies? What are your recommendations for future investigations?

Final conclusion

All of the aims of the thesis were achieved. The doctoral candidate presented the results of systematic research in a very reliable way, proposed his interpretations and presented discussions with prospects for further research. On the basis of the assessment presented, I conclude that the dissertation meets the conditions and requirements for doctoral dissertations specified in the current Act of 20 July 2018 on Higher Education and Science (with subsequent amendments). The reviewed doctoral thesis is an original study of the author and contributes to the field of Earth and Environmental Sciences. I therefore propose to admit Mr Dhanushka Devendra, MSc, to the next stages of the PhD process.

Jarosław Tyszka