Eötvös Loránd University
Doctoral School of Environmental Sciences
Environmental Physics Program

Topál Dániel

Large-scale circulation driven changes in the Arctic cryosphere and Central-Europen hydroclimate - with insights from paleoclimate

-theses of doctoral dissertation-

Advisors: István Gábor Hatvani Ph.D. habil. and Zoltán Kern Ph.D.

External consultant: Prof. Qinghua Ding (University of California Santa Barbara)

Chair of Doctoral School: Prof. Tamás Turányi

Programleader: Ákos Horváth, Ph.D. habil

Budapest, 2022

Table of contents

Introduction

Anthropogenic activities advance the level of CO_2 concentrations in the atmosphere at a rate of approximately 1% per year. Associated changes in the global mean surface temperature are likely to have emerged from unforced natural processes of the climate system i.e., from internal variability (Hawkins et al. 2020). The dramatic reduction in boreal summer (June-July-August, JJA) Arctic sea-ice cover and thickness as well as the melting of the Greenland Ice Sheet (GrIS) since the 1990s have become iconic symbols of on-going climate change (IPCC, 2021). The emergence of regional forced changes from the underlying ‘noise’ in the Arctic is less certain (Ding et al. 2014;2017;2019; Topál et al. 2022), nonetheless, a significant – yet uncertain – portion of the observed Arctic warming is undoubtedly attributable to anthropogenic forcing and its associated positive feedbacks, collectively known as Arctic amplification (AA; Deser et al, 2010; Screen and Simmonds, 2010; Notz and Stroeve, 2016; Screen et al, 2018).

Existing linkages between observed Arctic JJA atmospheric circulation anomalies – featuring a low-frequency trend toward mid-to-upper-tropospheric anticyclonic wind anomalies above Greenland and the Arctic Ocean – and September sea-ice variability over the past four decades are apparent (Ding et al, 2017;2019). The GrIS is the single largest contributor to barystatic sea-level rise (Hofer et al. 2020). Similar to Arctic sea-ice, it exhibits symptoms of accelerated ice loss (Hanna et al. 2020; IPCC 2021) with serious climatic and ecological consequences. The anthropogenically-forced response – multi-model means, or single-model large ensemble means – of GrIS surface conditions in CMIP5/6 climate models is mostly consistent with surface temperature and mass balance changes derived from satellite-based observations and reanalyses, nevertheless, concerns have also been raised that the underlying physical mechanisms responsible for enhanced GrIS melting may differ in observations and models, hence models might produce a portion of GrIS warming for wrong reasons (Hanna et al. 2020; Topál et al. 2022). Hence, despite tremendous research efforts over past decades, mechanisms of AA and

Arctic climate change are still difficult to pinpoint (Goosse et al. 2018).

Aims

Based on the above arguments, I plan to dive deeper and aim to provide a better understanding of the mechanisms responsible for accelerating GrIS melting in observations and multiple climate model simulations. These motivated my PhD research to explore the Arctic cryosphere changes' driving mechanisms from new lens.

Materials and methodology

The methods used comprised the following:

- descriptive statistics and "elementary" time series analyses to get an overview on the data
- principal component analyses; linear regression analysis; Mann-Kendall test statistics; maximum covariance analysis to explore connections between meteorological fields
- introducing the Arctic/Greenland streamfunction index to quantify the sensitivity of Arctic/Greenland

surface conditions to large-scale atmospheric circulation changes (Topál et al. 2022)

- a new technique to constrain model sensitivity to atmospheric circulation and its impacts on the future ice-free Arctic projections (Topál and Ding in prep)

Results

(1) My results suggest that an atmospheric process, partially originating from internal variability, is a significant contributor to sea-ice changes not only in the past decades, but also under future emissions scenarios.

(2) To somewhat circumvent model sensitivity issues, making use of the wind-nudging framework, I quantified the wind-driven response of Greenland Ice Sheet (GrIS) melting with implications to global sea-level rise. A substantial portion, –71.7 Gt yr^{-1} $decade^{-1}$ (out of the –132.8 Gt yr^{-1} $decade^{-1}$) total ice mass change equaling ~0.2 mm yr^{-1} $decade^{-1}$ sea-level rise acceleration relates to wind-induced adiabatic warming between 1990 and 2012, which holds potential for atmospheric circulation to affect the rate of sea-level rise to a similar extent in the coming decades.

(3) Paleoclimatic evidence reinforces that the significant enhancement of GrIS melting between 1990 and 2012 and associated acceleration in the rate of sea-level rise have been a manifestation of low-frequency variability in the climate system, arising from decadal tropical SST variability.

(4) Lessons learnt from the nudging experiments lead to the next steps to actually interpret the model issues in terms of the transient Arctic climate sensitivity. The misrepresented sensitivity of Arctic sea-ice and the GrIS to large-scale winds in climate models prioritizes a need to refocus model evaluation efforts from expecting the models to match observed surface warming rates in their forced responses and instead assess model skill in simulating the observed sensitivity to overlying circulation changes. The global mean temperature response to CO_2 forcing seems insufficient to scale the Arctic climate response. The models' low sensitivity to atmospheric forcing (compared with observations) can result in too strong Arctic warming- and a high sea- and land-ice sensitivity to anthropogenic forcing if the priority

criteria to evaluate model performance is based on matching the simulations with observations.

(5) I show that the main difference between the modelled and observed Arctic sea- and land-ice sensitivity to atmospheric circulation is that the models' forced responses do not favour a low frequency change in the rotational component of Arctic winds since under global warming scenarios they exhibit rather horizontally uniform sea surface temperatures response in the tropics. Hence the main source to create strong rotational winds in the high latitudes through Rossby-wave dispersion is obstructed.

(6) Accounting for this discrepancy I find that the likely probability of a seasonally ice-free Arctic and widespread GrIS melting is delayed by 9–15 years, and it is not likely to see an ice-free summer before 2050. Hence, improved simulation of the Arctic's observed sensitivity to large-scale atmospheric circulation-driven changes in climate models may provide a means of significantly improving

predictions of the GrIS's future contribution to global environmental crises.

(7) My results suggest that those models that perform best in Central Europe to capture decadal hydroclimate variability are currently not being used to force regional climate model (RCM) simulations in East Central Europe, which may lead to spurious projections of future drying in our region and false attribution of internal variability driven changes to a forced hydroclimate response. My results suggest that the difference between the constrained ensemble's and the six single-model initial condition large ensembles' (SMILE) future summer precipitation trends may be attributable to land-atmosphere coupling discrepancies between the models. Physical differences between models thus plays an important role in regulating future summer hydroclimate uncertainty and calls for caution when interpreting future summer precipitation projections of the state-of-the-art SMILE simulations.

Acknowledgements

I would like to express my gratitude to my supervisors István Gábor Hatvani & Zoltán Kern and to Attila Demény for endless personal and scientific support. I thank Qinghua Ding for his tremendous advises and professional help. I am further thankful to Tímea Haszpra, Mátyás Herein, Tamás Bódai, Thomas Ballinger, Edward Hanna, Xavier Fettweis and others whose insights have greatly contributed to my scientific development.

Published papers written in the framework of this Ph.D.

JOURNAL PAPERS, SCIENTIFIC PEER-REVIEWED

Topál, D, Ding, Q, Ballinger, TJ et al. (2022) Discrepancies between observations and climate models of large-scale wind-driven Greenland melt influence sea-level rise projections. *Nat Commun* **13**, 6833 https://doi.org/10.1038/s41467-022-34414-2

Topál, D, Ding, Q, Mitchell, J, Baxter, I, Herein, M, Haszpra, T, Luo, R, Li, Q, (2020a). An Internal Atmospheric Process Determining Summertime Arctic Sea Ice Melting in the Next Three Decades: Lessons Learned from Five Large Ensembles and Multiple CMIP5 Climate Simulations, *J Clim.* **33**(**17**), 7431-7454. https://doi.org/10.1175/JCLI-D-19-0803.1

Topál, D, Hatvani, IG, Kern, Z, (2020b) Refining projected multidecadal hydroclimate uncertainty in East-Central Europe using CMIP5 and single-model large ensemble simulations. *Theor Appl Climatol* **142**, 1147-1167. https://doi.org/10.1007/s00704-020-03361-7

Topál, D & Ding, Q (in prep) Constrained model sensitivity recalibrates projected Arctic climate change. in review in *Nat Clim Change*

Selected references

Deser, C, Tomas, R, Alexander, M, Lawrence, D (2010) The Seasonal Atmospheric Response to Projected Arctic Sea ice Loss in the Late Twenty-First Century. *J Clim*, **23**, 333-351. https://doi.org/10.1175/2009JCLI3053.1

Ding, Q et al. (2017) Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. *Nat Clim Chang* **7**, 289-295. https://doi.org/10.1038/nclimate3241

Ding, Q, Schweiger, A, L'Heureux, M et al. (2019) Fingerprints of internal drivers of Arctic sea ice loss in observations and model simulations. *Nat Geosci* **12**, 28-33. https://doi.org/10.1038/s41561-018-0256-8

Ding, Q, Wallace, JM, Battisti, DS et al (2014) Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland. *Nature* **509**, 209-212. https://doi.org/10.1038/nature13260

Goosse, H, Kay, JE, Armour, KC et al. (2018) Quantifying climate feedbacks in polar regions. *Nat Commun* **9**, 1919. https://doi.org/10.1038/s41467-018-04173-0

Hanna, E et al. (2020) Mass balace of the ice sheets and glaciers – progress since AR5 and challenges, *Earth Sci Reviews* **201**, 102976. https://doi.org/10.1016/j.earscirev.2019.102976

Hawkins, E, Frame, D, Harrington, L et al. (2021) Observed emergence of the climate change signal: from the familiar to the unknown, *Geopys Res Lett* **47**(6) e2019GL086259, https://doi.org/10.1029/2019GL086259

Hofer, S et al. (2020) Greater Greenland Ice Sheet contribution to global sea level rise in CMIP6. *Nat. Commun.* **11**, 6289. https://doi.org/10.1038/s41467-020-20011-8

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

Notz, D, Stroeve, JC (2016) Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission. *Science*, **354**(6313), 747-750. DOI: 10.1126/science.aag2345

Screen, J.A., Deser, C., Smith, D.M. et al. (2018) Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models. *Nature Geosci* **11**, 155–163. https://doi.org/10.1038/s41561-018-0059-y

Screen, JA & Simmonds, I (2010) The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature* **464,** 1334–1337. https://doi.org/10.1038/nature09051