Interannual and Intraannual Regional Variability in Forest Phenology and Its Influence on Boreal Permafrost Thermal and Hydrological Dynamics

Where has the Far North's Future Already Happened?

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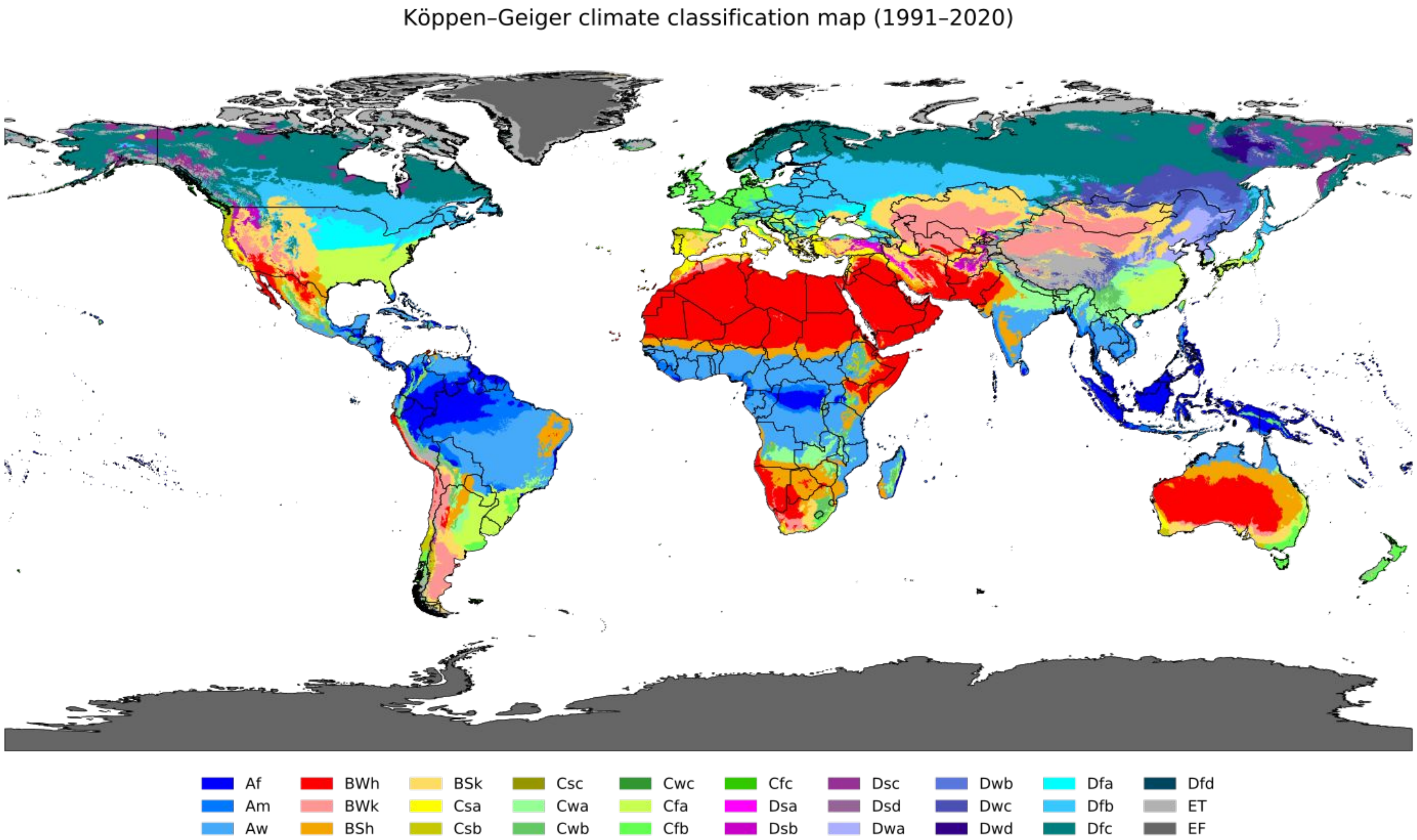
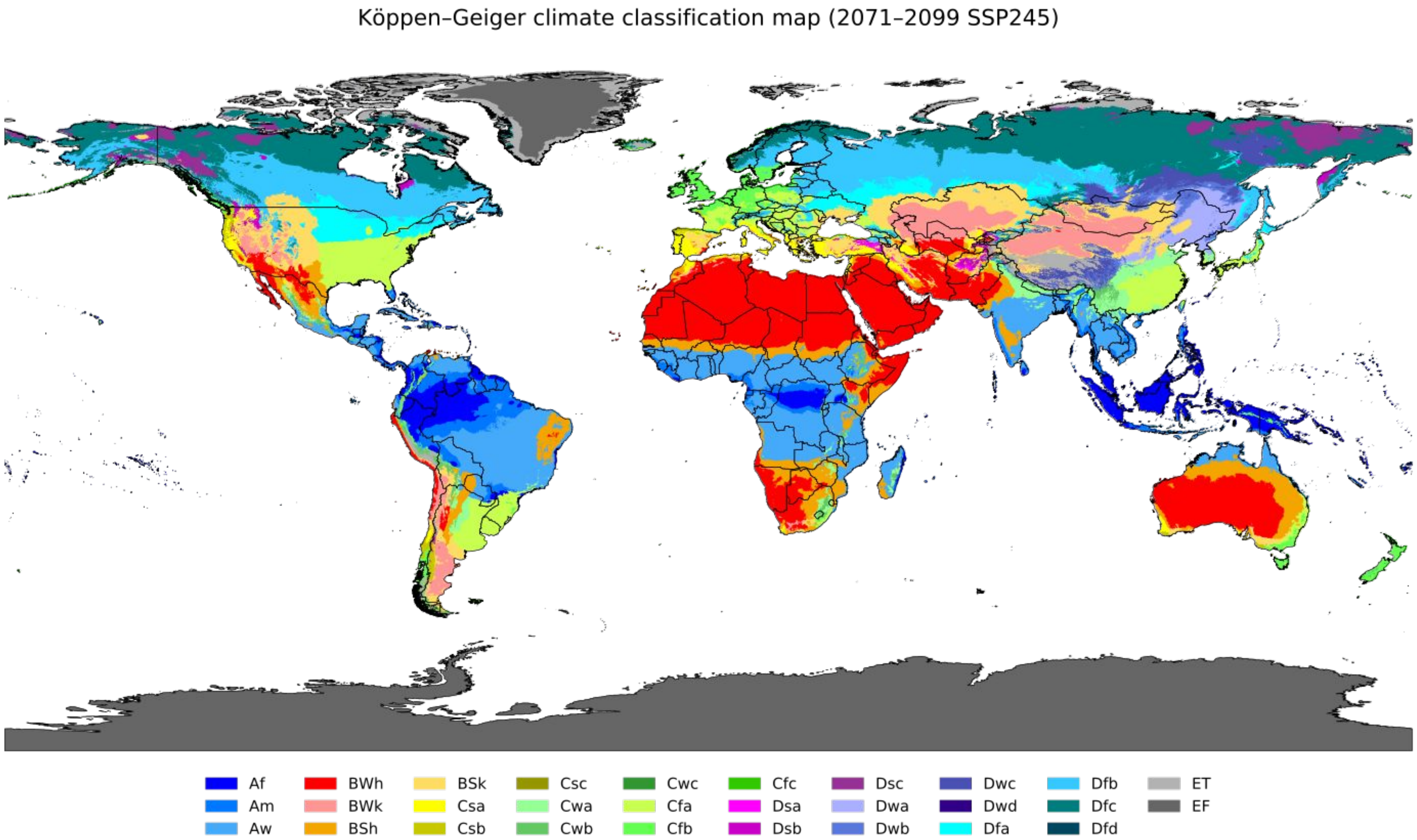
Introduction

Climate Change Fundamentals

- Shared Socioeconomic Pathways (SSPs): climate change scenario projections by Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2021)
- SSP2-4.5 (intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100) most likely (HAUSFATHER & PETERS, 2020)
- likely warming by 2100: 2.1 – 3.5 K (IPCC, 2021)
- climate zones shift polewards in response (BECK et al., 2018)
- polar amplification: warming more pronounced in polar regions as compared to the global average (LEE, 2014)



Source: Beck et al. (2023): High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections, Scientific Data 10:724, doi:10.1038/s41597-023-02549-6.



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Introduction

Concept

- records of past and models of future climate data are available worldwide
- if climate zones shift towards the poles, records should show climatic changes in the south* of a study region analogous to shifts predicted to occur in the future further north*
- enables extrapolation of related changes, space for time substitution

“Over the next n years, this area in the north is expected to experience the following climatic changes. Over the past n years, this area in the south* has already experienced analogous changes. Therefore, if we want to see what the northern* area will look like in the future, we should look at what the southern* area looks like now, and how it has changed.”*

*relative to the northern hemisphere

Introduction

Research Objectives

- How well are predicted climatic changes for the future of the north of a study area in the northern hemisphere reflected in the past changes of the south of the same study area?
- Assuming such areas of correspondence exist, how well can they be used to extract related bioclimatic data to further extrapolate the future of the north of the study area?

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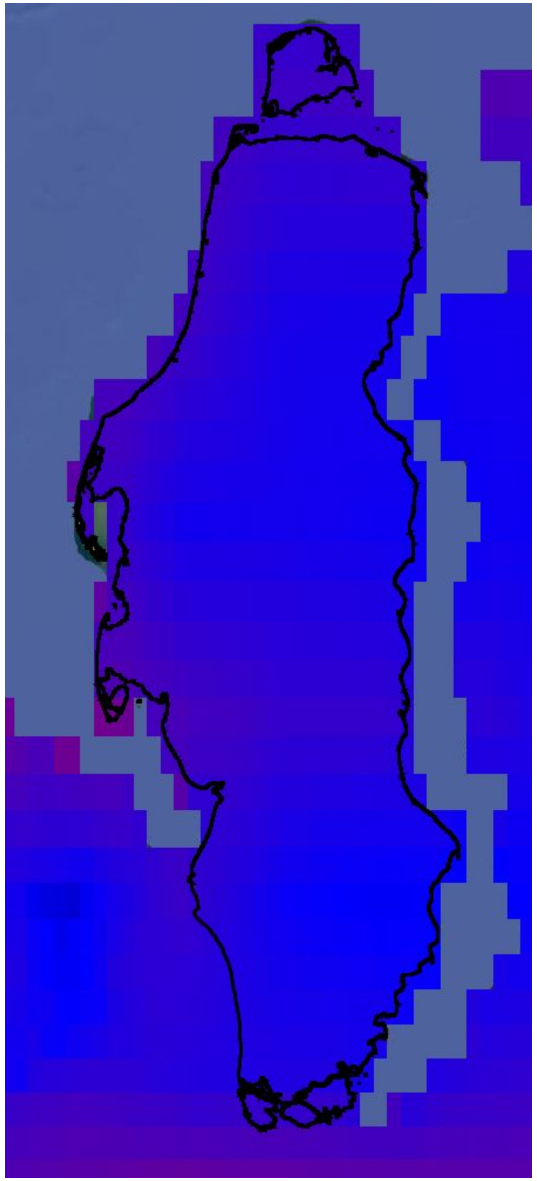
Methodology

Study Site Selection

- requirements:
  - north-south gradient
  - relatively even terrain
  - continuous permafrost

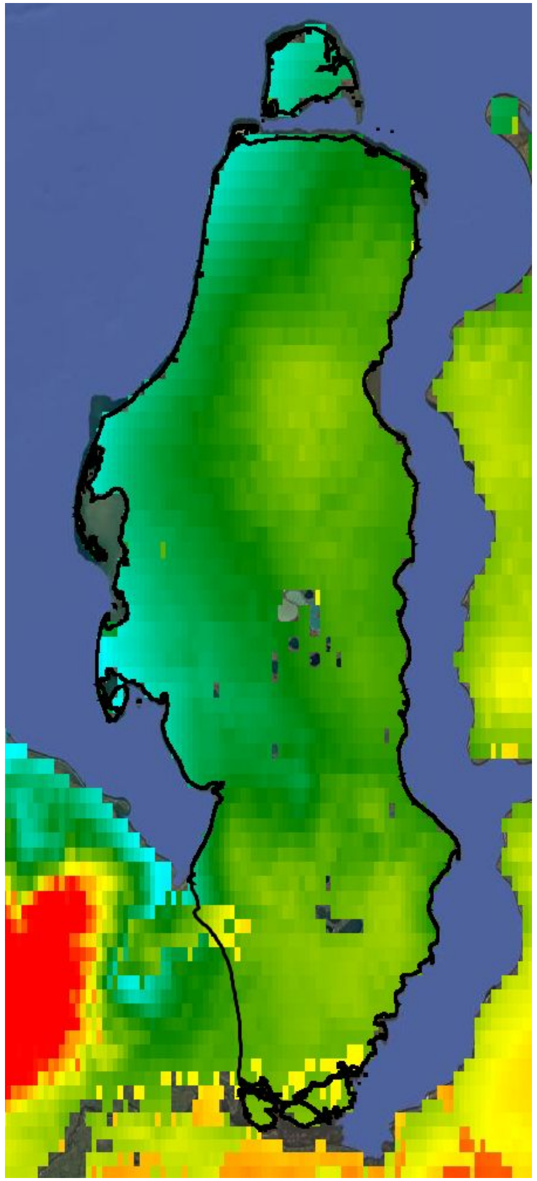
- choice:
  - Yamal Peninsula (northern Siberia)
  - ~700km north-south extent



Methodology

Data

- climate projections for SSP2-4.5
    - NASA Earth Exchange Global Daily Downscaled Climate Projections
    - based on Coupled Model Intercomparison Project Phase 6 (CMIP6) (EYRING et al., 2016)
    - January 1950 – December 2100
    - humidity, precipitation, radiation (short- and long wave), wind speed, air temperature metrics
    - used for classification of past, present, and future climatic conditions, as well as change detection



Methodology

Data

- extrapolation of snow characteristics
  - NASA Famine Early Warning Systems Network Land Data Assimilation System (FLDAS)
  - January 1982 – ongoing (used until March 2025)
  - snow cover fraction (SCF), snow depth (SD), snow water equivalent (SWE)
  - used to calculate historical changes in snow characteristics

Methodology

Data

- extrapolation of biomass
  - ESA Biomass Climate Change Initiative (CCI)
  - 2007, 2010, yearly 2015 – 2022

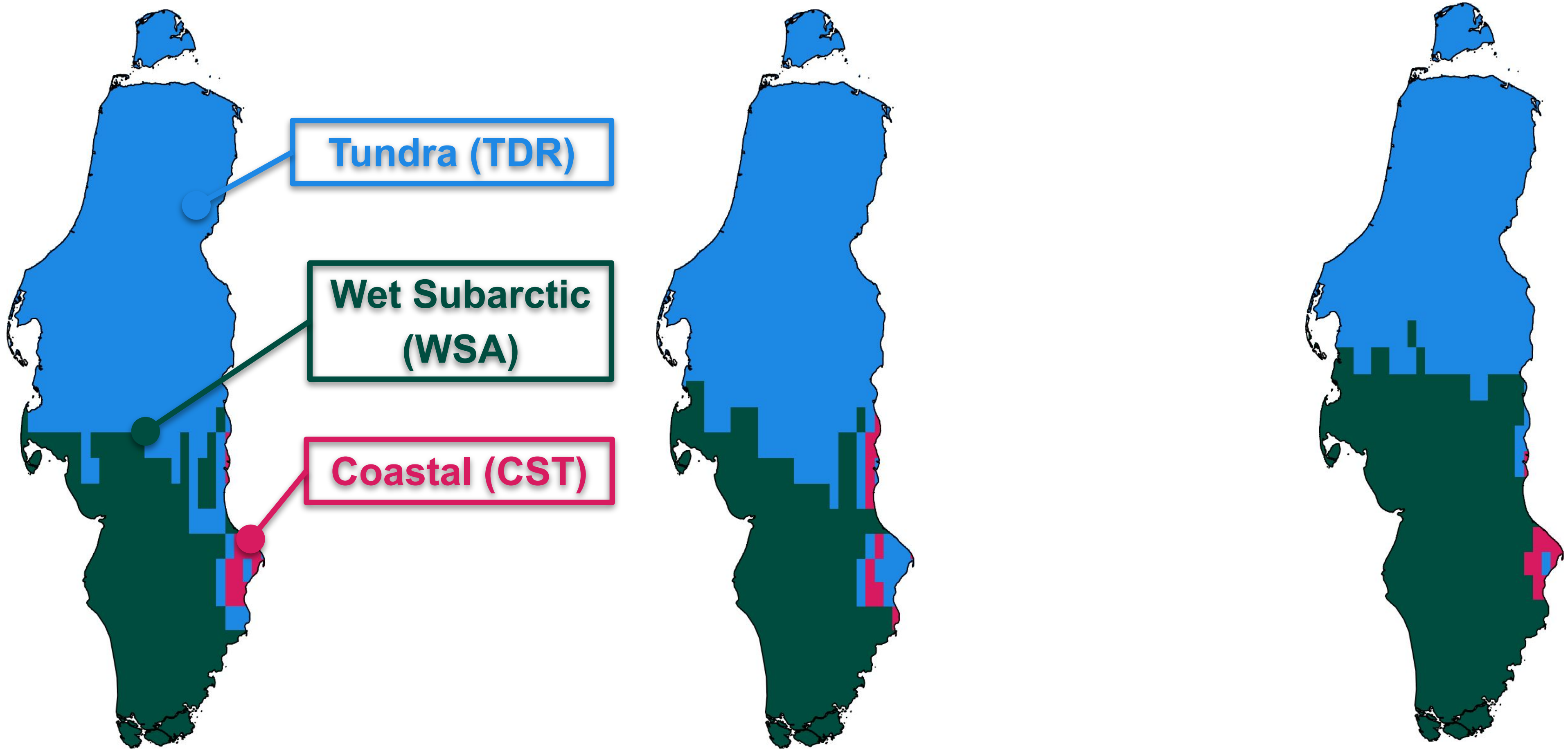
    → bottleneck on research time frame
  - above-ground biomass [t/ha]
  - used to calculate historical changes in biomass

Methodology

Processing

- local climatic classification via k-means clustering for 2007 ("past"), 2022 ("present"), and 2037 ("future") CMIP data
  - hyperparameter tuning → three classes in all cases
- class assignment is pseudorandom → correspondence defined on best-fit basis
- calculation of unified set of average cluster centroids to ensure intercomparability
- classification of all time steps using unified centroids
- calculation of 2007 – 2022, 2022 – 2037 climatic classification change maps
- calculation of 2007 – 2022 changes in snow characteristics and biomass
- extraction of associated historical changes in snow characteristics and biomass per class change type

Results

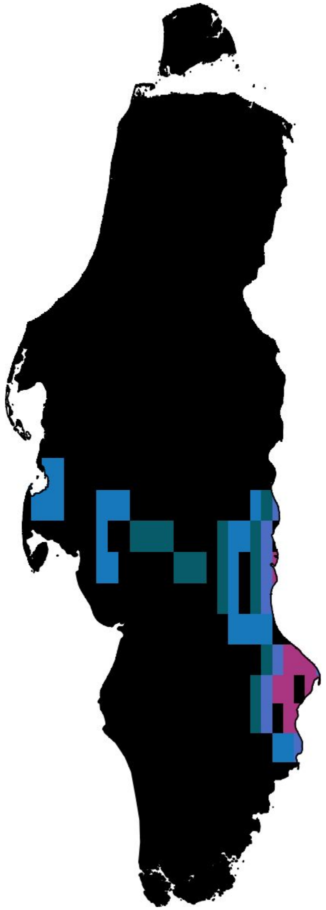


2007 CMIP data

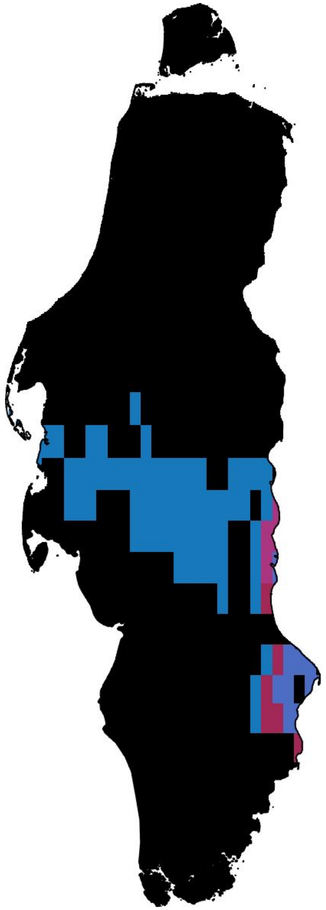
2022 CMIP data

2037 CMIP data (predicted)

Results

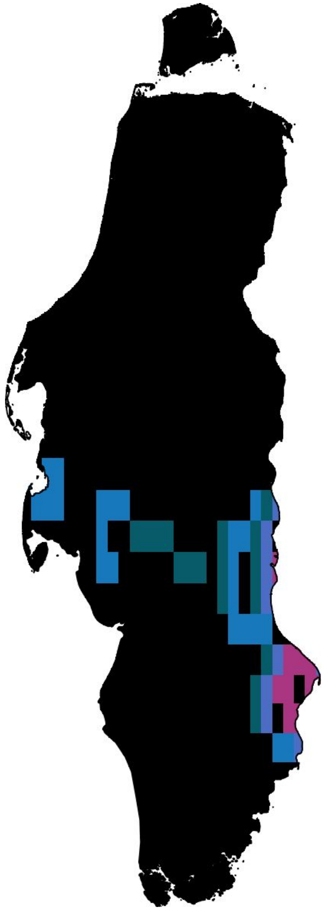


Past Change
2007 – 2022

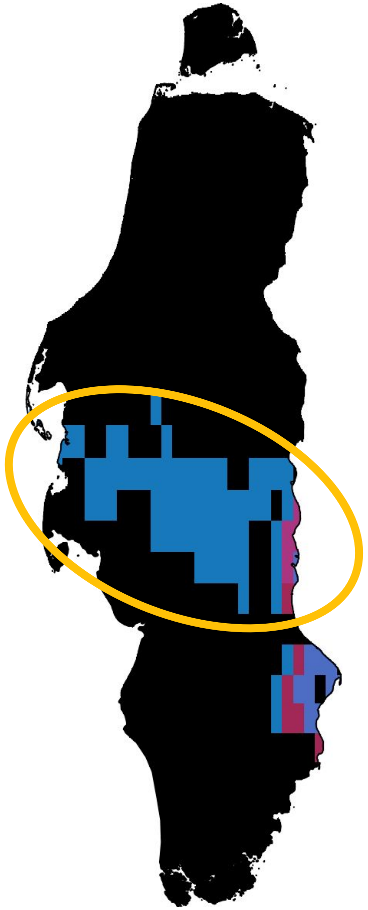


Future Change
2022 – 2037

Results



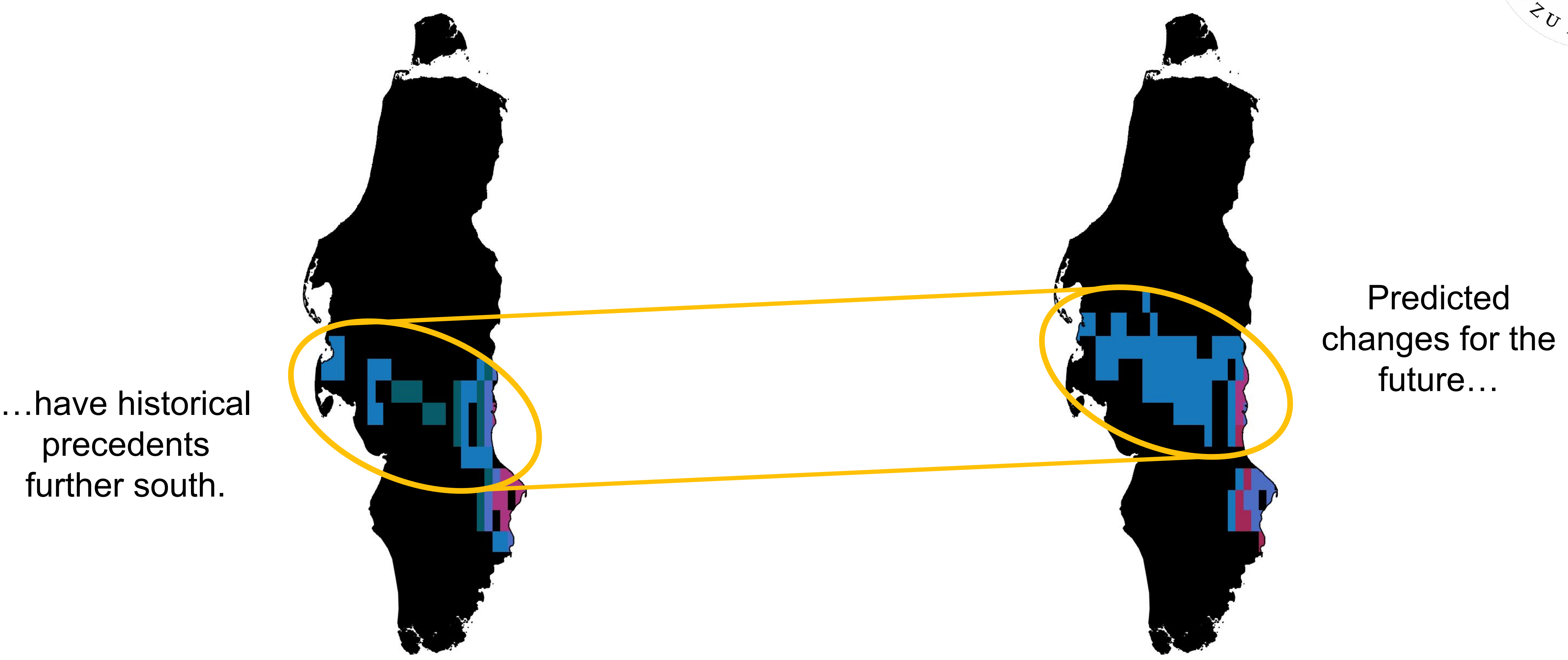
Past Change
2007 – 2022



Future Change
2022 – 2037

Predicted changes for the future…

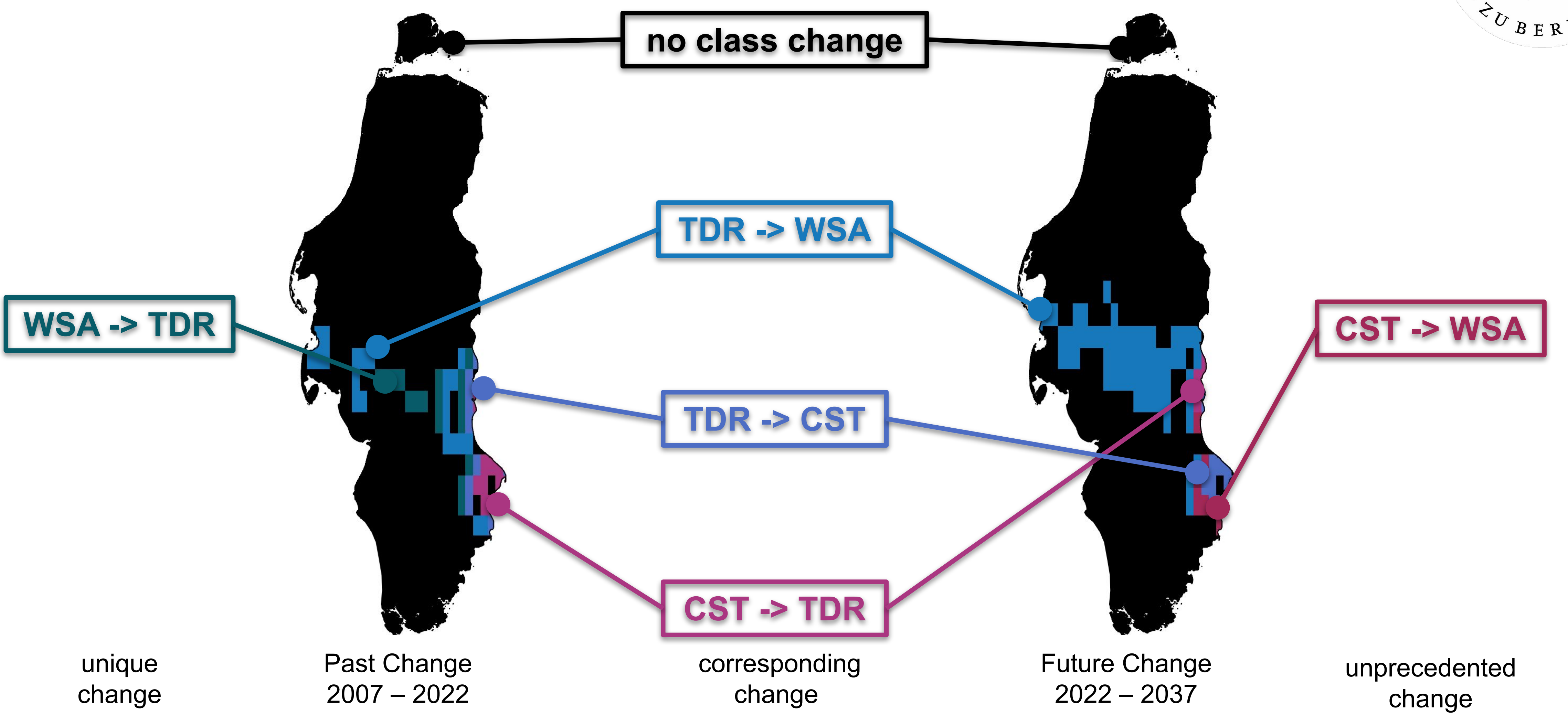
Results



Past Change
2007 – 2022

Future Change
2022 – 2037

Results


no class change
TDR -> WSA
WSA -> TDR
TDR -> CST
CST -> WSA
CST -> TDR
unique
change
Past Change
2007 – 2022
corresponding
change
Future Change
2022 – 2037
unprecedented
change

Results

Class Change	Snow Cover Fraction [%pt]	Snow Depth [cm]	Snow Water Equivalent [kgm^{-2}]	Biomass [t/ha]
no class change	-2.5	-11.5	-31.174	-0.046
TDR -> WSA	+1.9	-4.4	-27.452	-0.007
TDR -> CST	+1.2	-1.7	-28.239	-0.049
WSA -> TDR	+2.4	-1.6	-25.657	-0.002
CST -> TDR	+0.9	-2.9	-29.980	-0.105
CST -> WSA	unknown	unknown	unknown	unknown

Conclusion

Discussion

- identified spatiotemporal patterns match expectations
    - change patterns as expected from bands of similar climatic conditions moving polewards

      → successful proof of concept
- clusters ~ Köppen climate zones → cluster boundaries as hotspots of change
    - CST cluster linked to settlements (Yaptik-Sale, Novy Port), correlation or causation?
- TDR → WSA class change dominates, expected to occur on wider scale in the future
    - absence of WSA → TDR in future predictions suggests further destabilisation of conditions
- class changes associated with CST are highly volatile, unlikely to reflect actual conditions
    - local anthropogenic influence and/or simulation artefacts

Conclusion

Discussion

- snow characteristics
  - generally declining, conforming with predictions of warming climates & Polar Amplification
  - surprising disconnect between snow cover fraction and snow depth
- unexpected generally prevalent decrease in biomass
  - Reasons? Sparse input data? Seed availability?
- inter-class trends persist within classes, too (as seen in “no class change” trends)
- some predicted changes in local climate lack historical precedent → uncharted waters

Conclusion

Outlook

- data compatibility considerations → how comparable are CMIP and FLDAS data?
  - preliminary results: general but inhomogeneous correlation between related variables
- cluster similarity → do clusters in snow characteristics overlap spatially with CMIP clusters?
  - preliminary results: generally similar, but FLDAS even more of a N-S gradient, no significant cluster of coastal outliers in the SE (CMIP CST class)
- modelling → can future snow characteristics and biomass be predicted based on CMIP predictions
  - preliminary results: Q-Q plots imply significant inaccuracies, models failing to capture dynamics; potentially due to input data incompleteness, coarseness; varying performance with regards to training data subset and response variable

Conclusion

Outlook

- extraction / extrapolation of other data
    - soil characteristics
    - other biomass proxies, e.g. vegetation indices, as satellite observations permit
- inclusion of further input data next to CMIP
    - e.g. topography, etc.
- variation the time frame
- application to different study areas
    - risk of inaccuracy if inhomogeneous conditions prevent “smooth” polewards shift
    - no guarantee of temporally consistent classes resulting from k-means clustering
- in-situ verification of clusters / change dynamics

Sources

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