



# Statistical modelling of varved lake sediment to reconstruct seasonal climate over the past 6000 years

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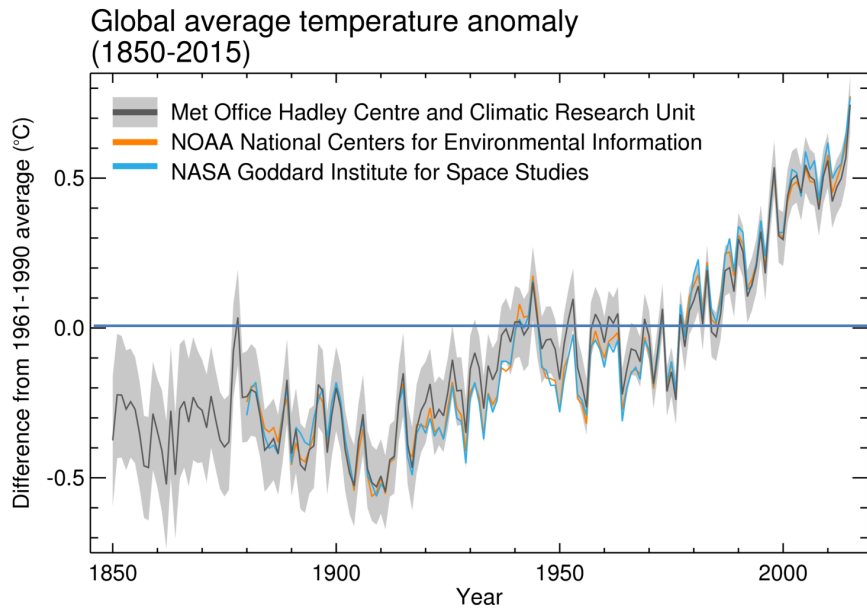
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# 2015 was the warmest year globally

“The American space agency NASA and the British Met Office confirmed that year 2015 was the warmest year globally **since measurements started in 1850.**”

*Dagens Nyheter 2016-01-20*



Global mean temperature 1850-2015  
(deviation from average 1961-1990)

How extreme is it in a longer time perspective?

How has the climate varied over longer time periods?



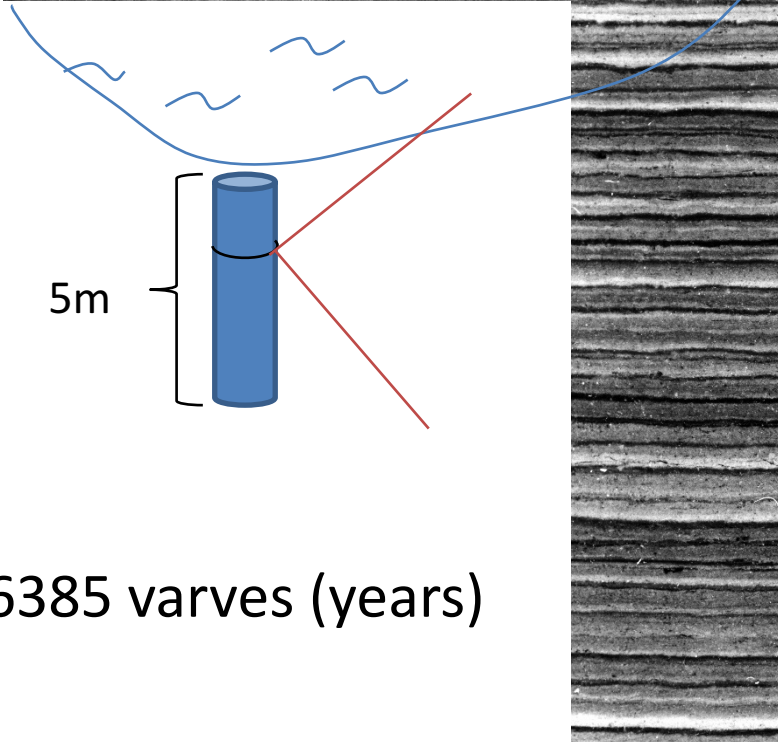
# Reconstructing climate

To reconstruct past climate at longer timescales, proxies are needed.

Proxies: Tree rings, ice cores, marine and *lake sediment cores*, ...

Our focus: Varved lake sediment

# Sediment from lake Kassjön



6385 varves (years)

Bright colour – minerogenic  
material

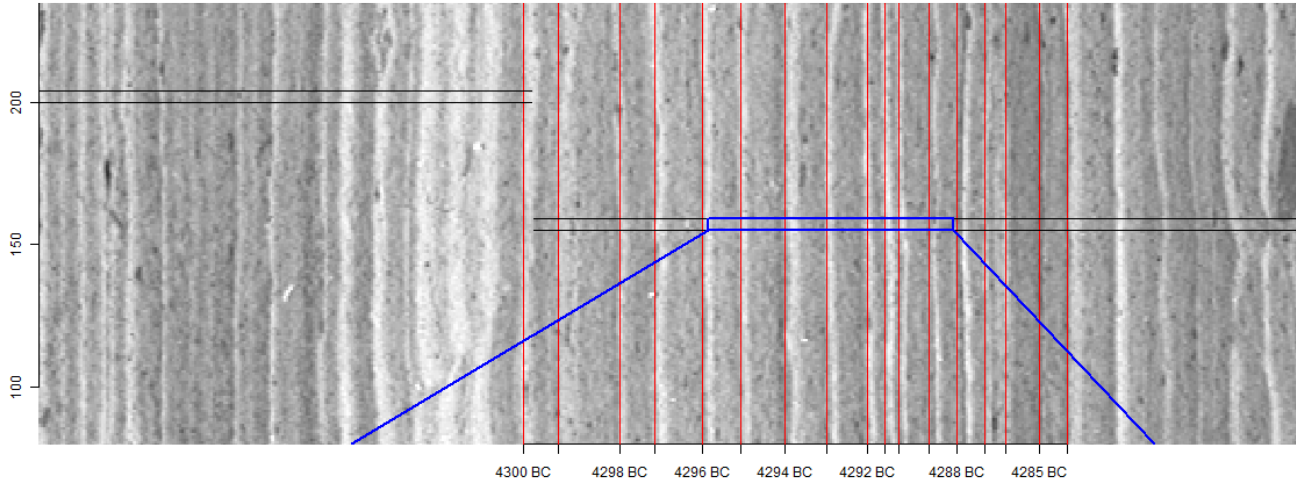
*winter*

Darker colour – organic  
material

*spring,  
summer,  
fall*



# Sediment from lake Kassjön



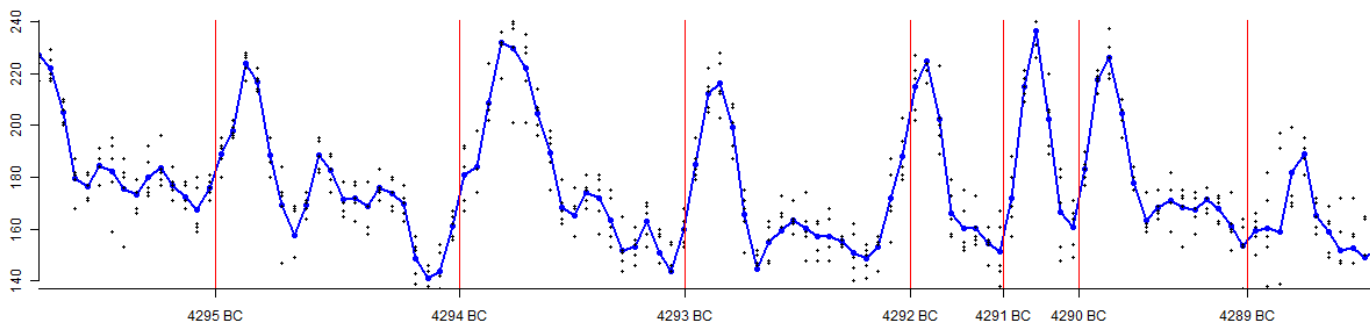
Similar seasonal profiles correspond to similar weather



Grey-scale values

Bright

Dark





# Weather - Climate

## Goals:

1. Group the seasonal profiles into similar types of *weather*
2. Group years into similar types of *climate*  
Climate – frequencies of weather, "average" weather

## Use functional clustering:

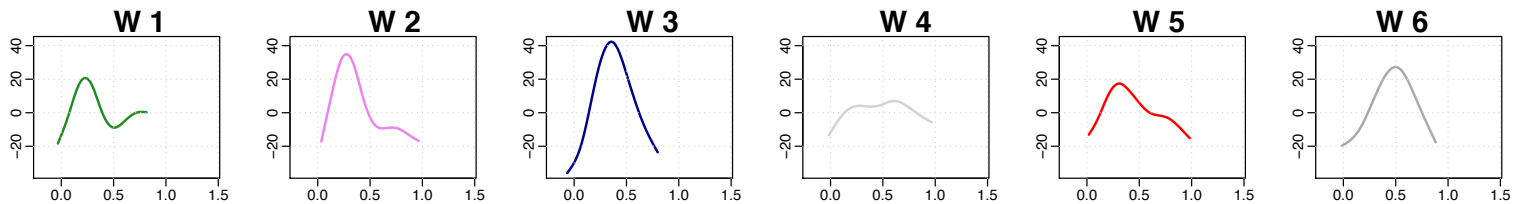
- describe profiles by **smooth functions** (cubic splines)
- Align the seasonal patterns (sedimentation process non-linear in time, e.g. synchronize spring peaks)
- Take dependence between years into account

# Cluster the seasonal profiles

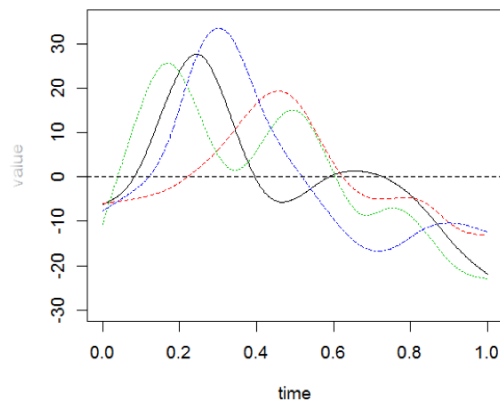
## **K medoid alignment** (Sangalli et al. 2010)

Simultaneously clusters and aligns

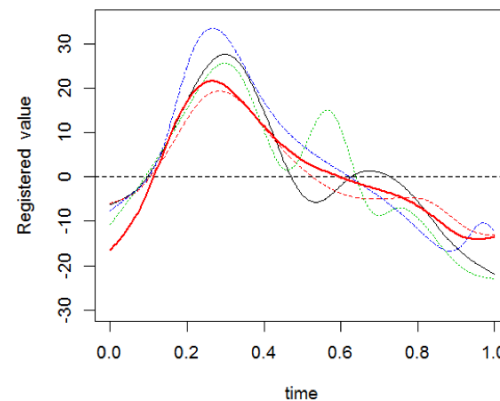
Weather-clusters of Kassjön



Original curves,  $x(t)$



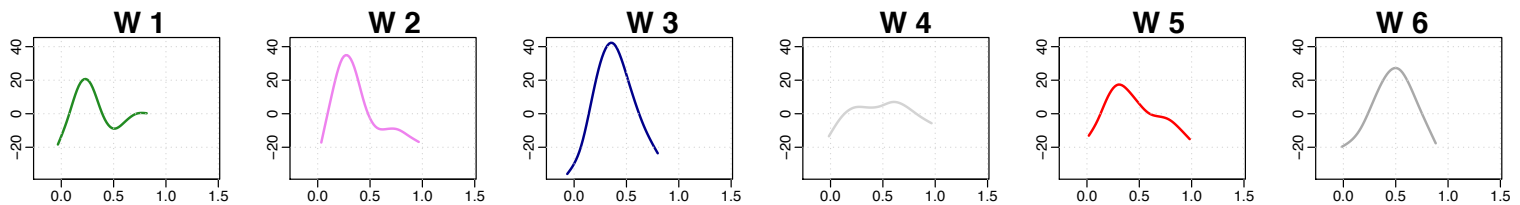
Aligned curves,  $x[h(t)]$



# Cluster the seasonal profiles

## **K medoid alignment** (Sangalli et al. 2010)

Simultaneously clusters and aligns

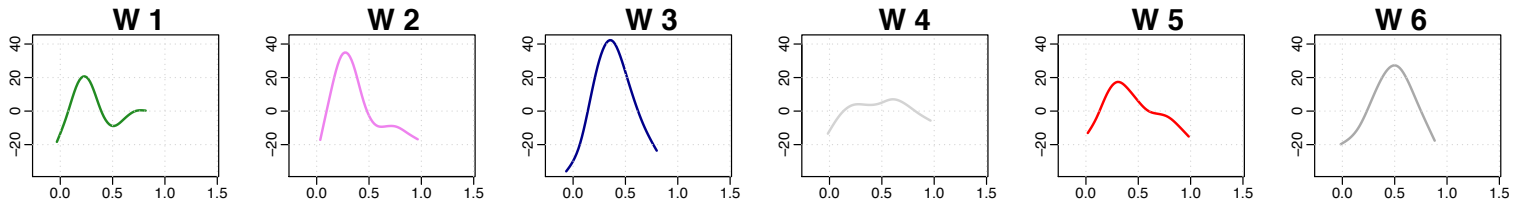


Winter temp:            cold                    cold                    -                    warm                    less cold                    coldest  
proxy

- Agricultural activities around Kassjön makes it difficult to compare with meteorological data the last few hundred years.
- Compare with a winter proxy reconstruction AD 500-1800 Leijonhufvud et al. (2010), port activities in Stockholm.



# Weather dynamics



Winter temp: cold  
proxy

cold

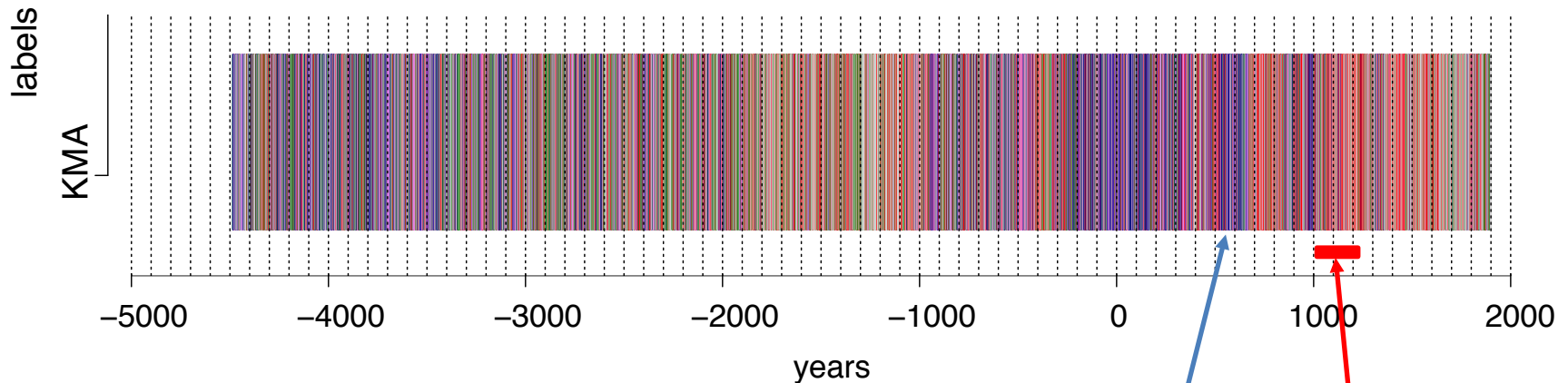
-

warm

less cold

coldest

## Time dynamics



Cold years 536, 540, 547, tree rings Altaj Sibiria and alps in Austria... (Büntgen et al., 2016)

Medieval warm period

# Clustering Climate

(frequencies of weather, "average" weather)

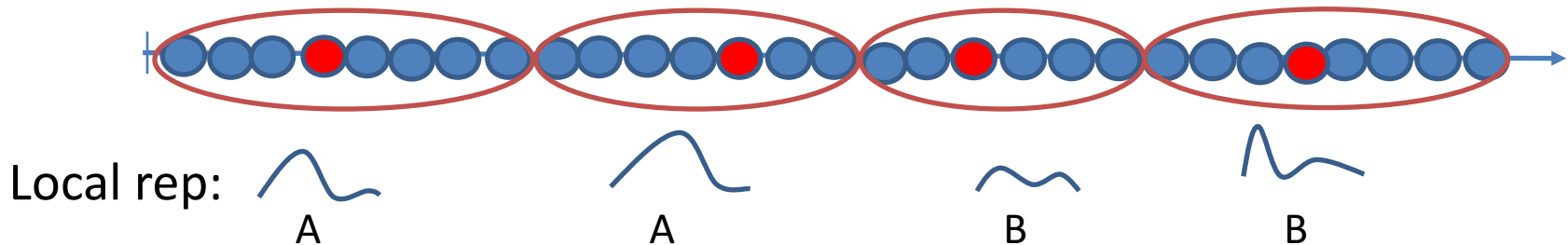
## Bagging Voronoi K medoid alignment (Abramowicz et al. 2016)

- takes dependence and misalignment into account when clustering.
- Associate to each year a latent label  $k = 1, \dots, K$  (climatic scenarios)



# Bagging Voronoi K medoid alignment algorithm

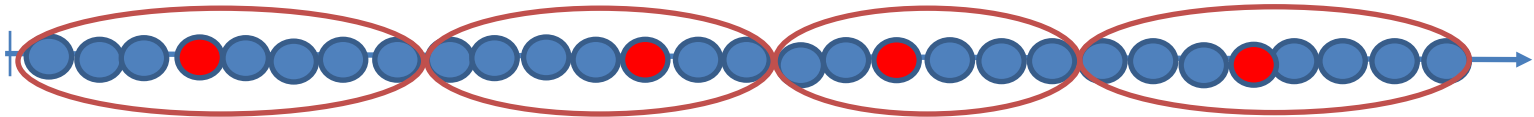
- Cluster local representatives of groups of consecutive years (random partition, expected size of groups is  $L$ ), taking misalignment into account.



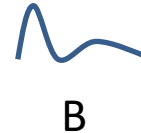
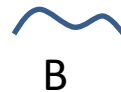
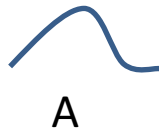
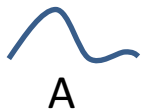
# Bagging Voronoi K medoid alignment algorithm

- Cluster local representatives of groups of consecutive years (random partition, expected size of groups is L), taking misalignment into account.
- Years in the same group get the same cluster label.

A A A A A A A A A A A A B B B B B B B B B B B B B B



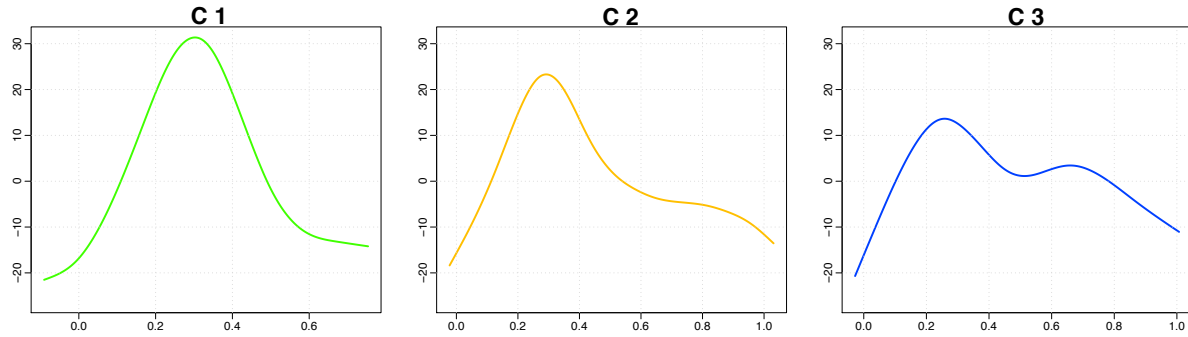
Local rep:



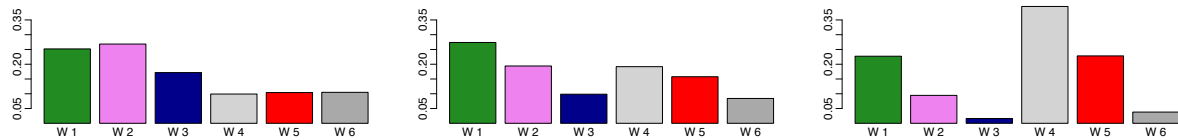
- Repeat procedure several times.
- Assign cluster label to each year by majority vote.

# 6 Climate clusters

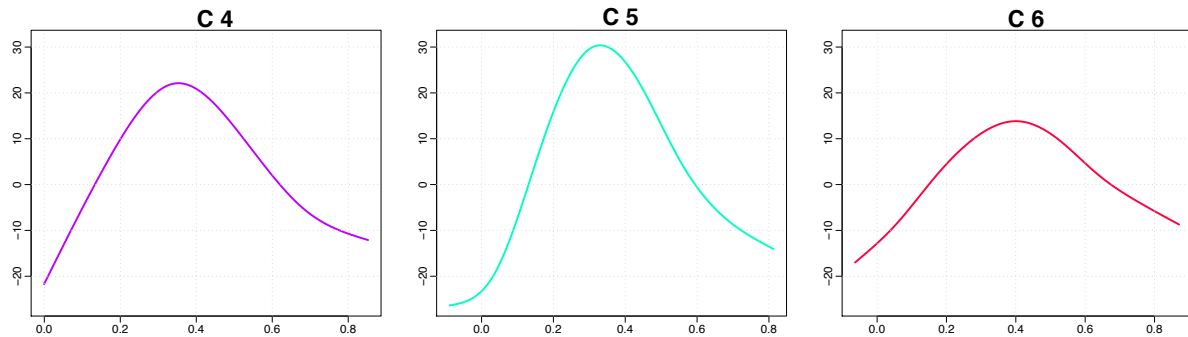
Cluster medoids



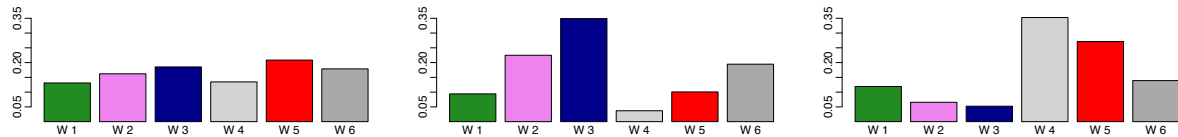
Frequencies of weather



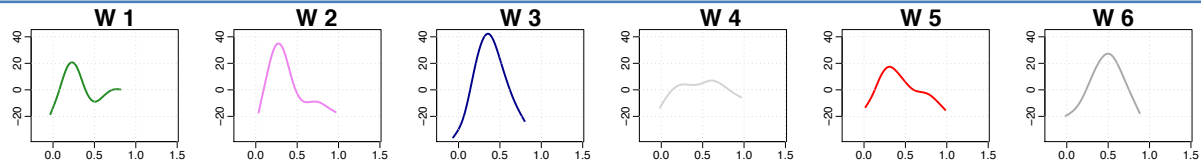
Cluster medoids



Frequencies of weather



“Weather”  
(6-medoid alignment)



Winter temp.

cold

cold

-

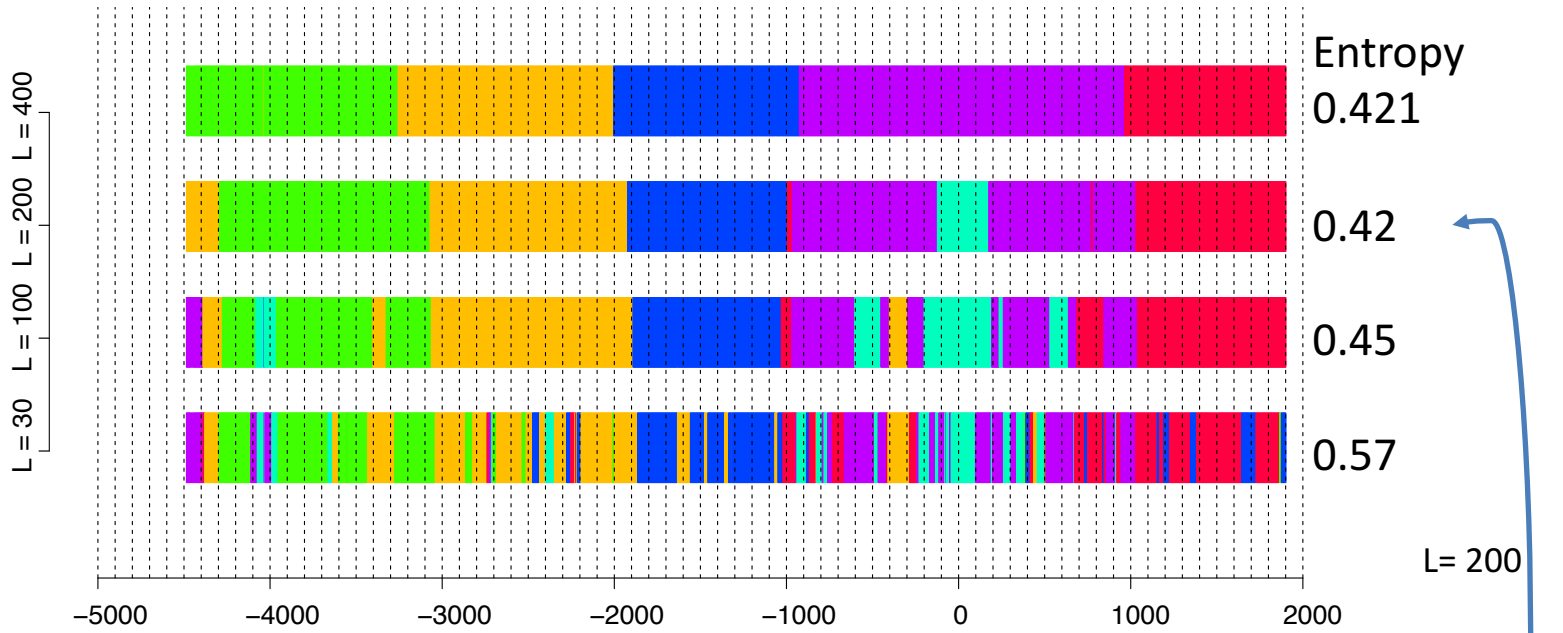
warm

less cold

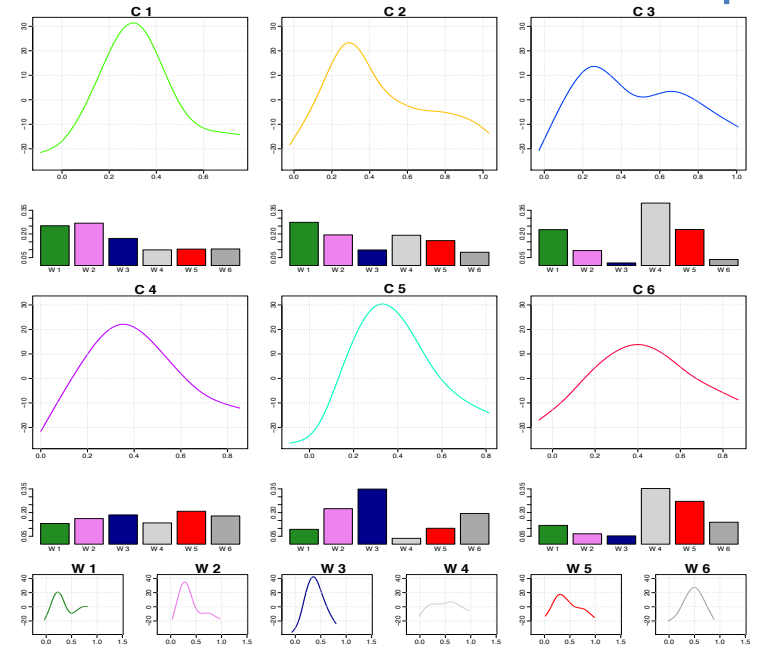
coldest



# Time dynamics for climate clusters on different scales



Low entropy indicates suitable L (local group size).



Winter temp: cold cold - warm less cold coldest



# Conclusions

- A novel non-parametric method to cluster dependent, misaligned functional data.
- Potential to detect latent structures.
- Applied to reconstruct *winter* climate 6400 years, from varved lake sediment, N. Sweden.
- Most proxies captures summer climate - varved lake sediment captures winter climate.
- Reconstruction of climate can be used to understand past climate fluctuations and to validate/calibrate climate models used to predict future climate.