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Regional climate modelling for wind farm optimization and control

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Background

Federal University of Pará
Bachelor's in Meteorology
Mar 2012 – Dec 2016

University of Nevada, Reno
Non-degree student (Atmospheric Sciences)
Jan 2015 – Dec 2015

National Institute for Space Research
Master's Degree in Meteorology
Mar 2017 – Dec 2018

KU Leuven
PhD in Science
Jan 2019 – Present

Content

- Research:

  1. Introduction :
     - Introduction
     - Research gaps
     - Research plan

  2. Current focus:
     - Methodology
     - Results
       - Quantile transform
       - Outlier removal

  3. Conclusion and future work

- Education:

  1. Papers
  2. Attended courses
  3. Conferences
  4. Courses to be followed

Introduction (Wind Farms)

➢ It is expected that the North Sea basin will see a massive expansion of large offshore wind farms over the next few decades.

Advantages:

I. stronger winds implying greater productivity

II. available area for installing the large wind parks

III. elimination of noise and visual impact on humans

IV. Clean Energy!

Existing and planned wind farms in the North Sea

Wind energy network (2019)

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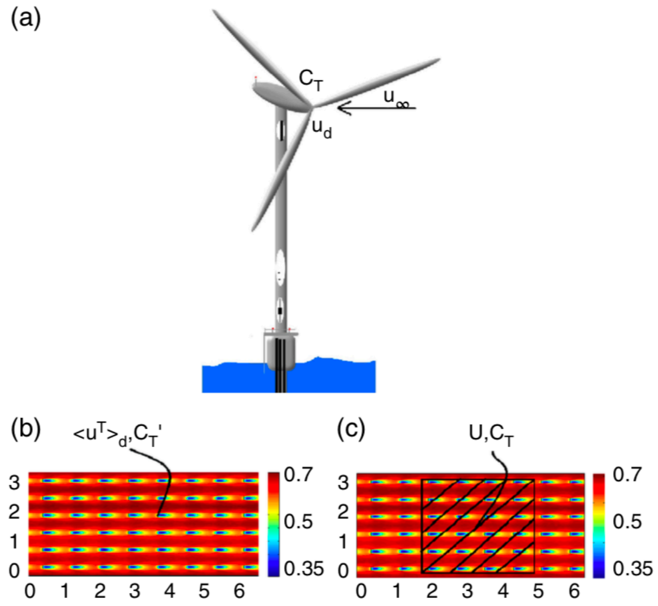
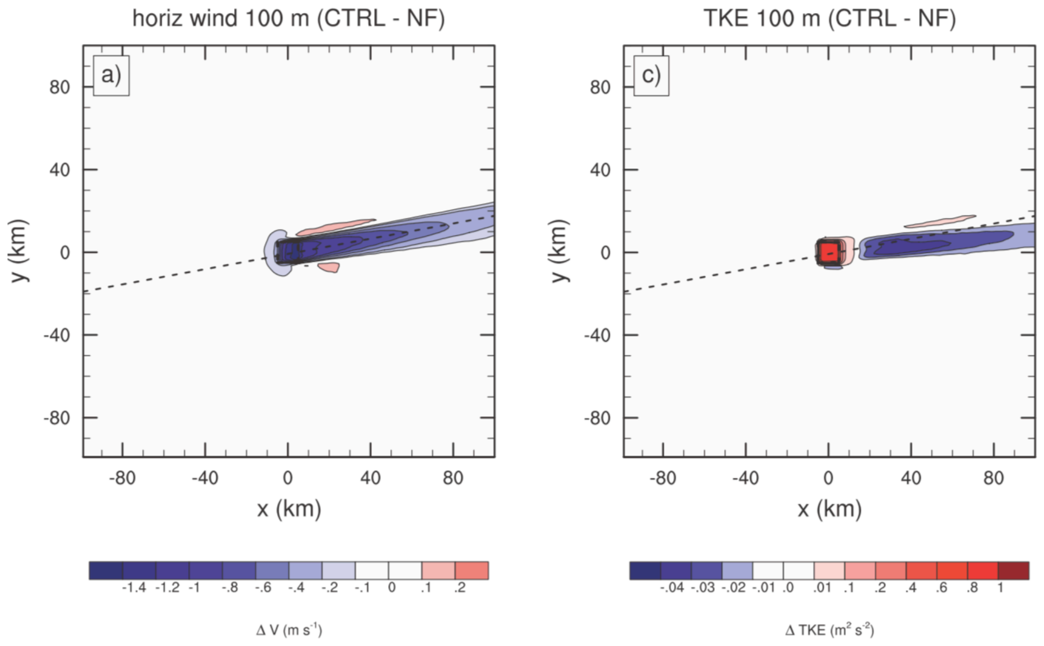
Introduction

- Wind farms can be parameterized in numerical models;
- LES models consider each wind turbine individually while RCM parameterize it;
- The resolution of a RCM is much coarser than a LES simulation;
- However, RCMs can help understanding the mesoscale effects on the wind farms;
- Fitch et al. (2012) proposed a parameterization for wind farms which is currently the most common one across different models;
- However, Chatterjee et al. (2016) found that the Fitch parameterization misrepresents turbulent dissipation in the BL.





Chatterjee at al. (2016)

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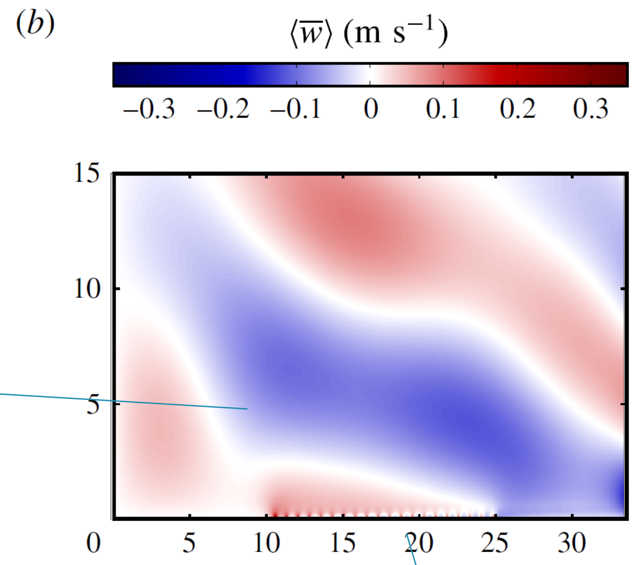
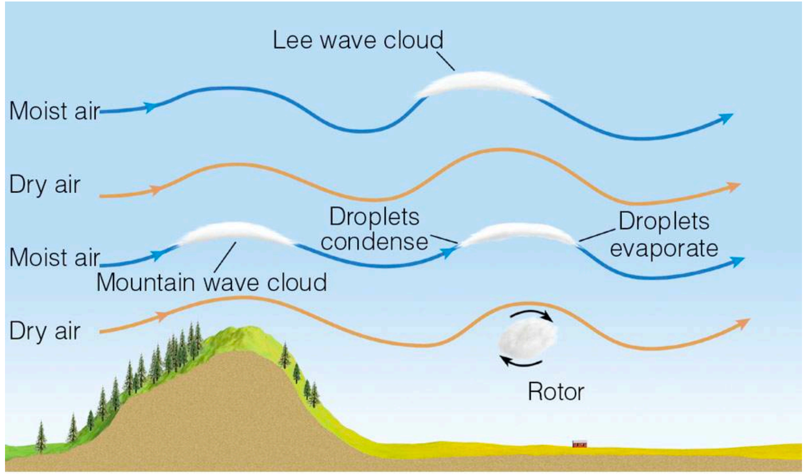
Introduction

- When running a LES or RCM model, we cannot select all the possible events since these simulations are expensive;
- The selection of “golden” cases can guide us in the understanding of how the wind farms impact the weather and climate;
- Usually most of the classifications taking in consideration only wind (speed and direction);
- However, wind farms can impact the weather and climate via excitation of gravity waves;
- Therefore, methods of classification need to consider more atmospheric variables (e.g. atmospheric stability, temperature inversions, etc.).



Upward flow deflection

Thickening of the BL above the wind farm



© 2007 Thomson Higher Education

Allaerts & Meyers, *J. Fluid. Mech.* (2017)

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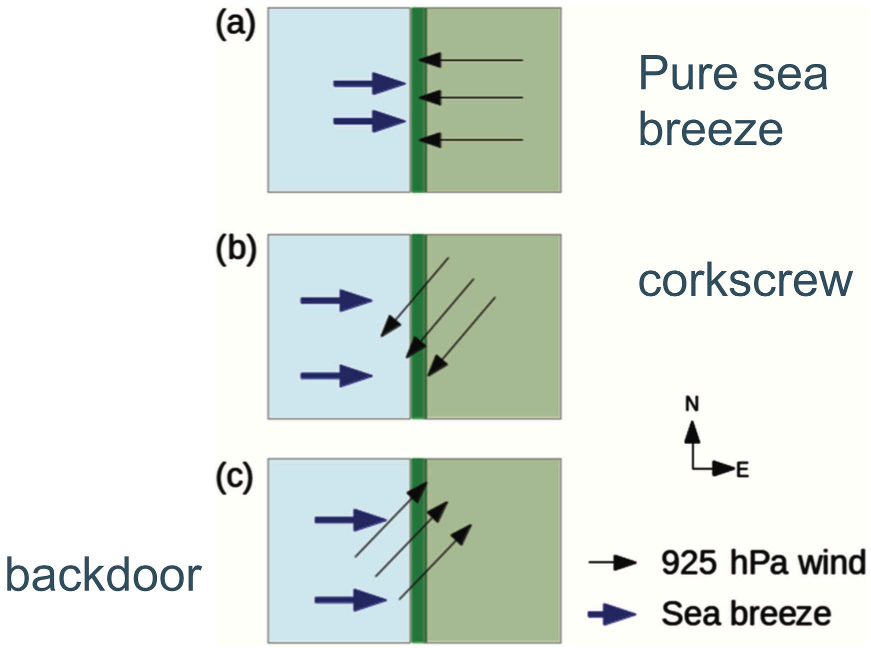
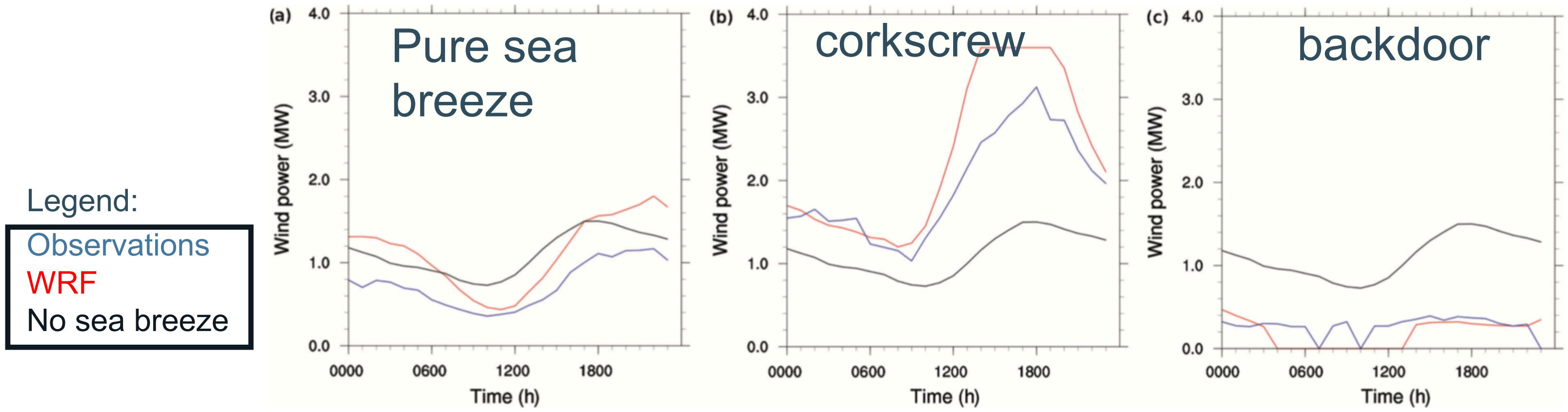
Introduction

- Another problem usually not considered when studying/planning wind farms is the effects of mesoscale systems;

- Steele et al. (2015) show that different types of breezes can affect the energy extraction.

- Therefore, **optimization and control** taking into account these effects are important!





Steele et al. (2015)

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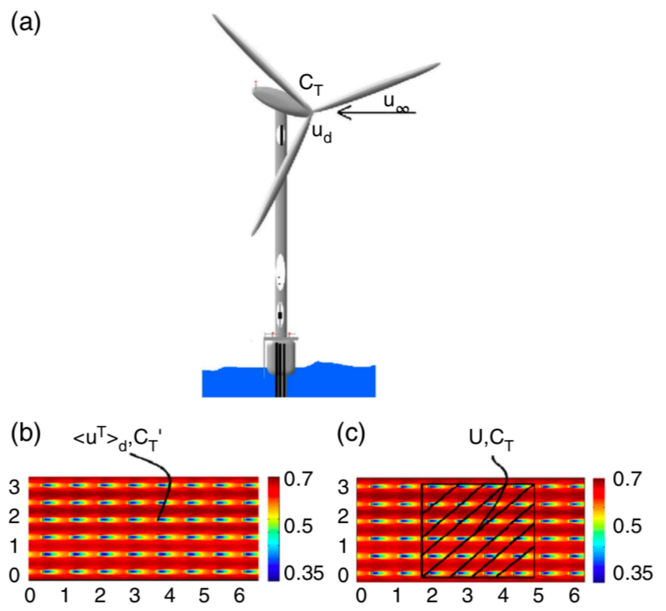
Introduction



- Another important effect that usually is not taking into account is the effects between wind farms;

- The effects between wind turbines is well know (e.g. wake effects);

- Optimization and control usually is done considering only the interaction between wind turbines, but could other nearby wind farms affect the energy extraction?

Chatterjee at al. (2016)

Research Gaps

- Although Chatterjee et al. (2016) applied the Fitch wind farm parameterization and found good results, the model still misrepresents turbulent dissipation in the BL;

  RQ: (How) can we improve the wind farm parameterization to make the model perform better compared to the LES simulations?

- Traditional classifications for atmospheric conditions rely only on wind direction, not taking into account other atmospheric variables;

  RQ: Can we select the main atmospheric conditions taking into account different atmospheric variables that affect the wind farms?

- Sea breeze and other mesoscale system effects on the wind-farm power extraction is still not well understood or in some cases unknow;

  RQ: Do mesoscale systems affect the wind farms? If so, how?

- Mesoscale effects have are not well investigated/considered in **optimization** and **control**;

  RQ: Should we consider mesoscale systems in optimization and control?

  RQ_2: Can we improve the energy extraction taking into account these systems?

- The interactions between big wind farms are not considered.

  RQ: How wind farms interact with each other? Does it affect energy extraction?

Research plan

- WP 1: Statistical overview of atmospheric conditions (**current**)
  - Development of a classification in order to select relevant cases based on atmospheric parameters.
- WP 2: Improvement of the turbine parameterization on COSMO
  - Improvement of the Fitch parameterization using wake models;
  - Couple the wake model into meso-scale simulations.
- WP 3: Study of the near-coast wind farms and coupling with sea breeze systems .
  - Evaluate and investigate the interactions between sea breeze and other mesoscales systems in the COSMO model;
  - Investigate these interactions over a 10 years period.
- WP 4: Evaluation of wind-farm interaction and sensitivity analysis of operational set points.
  - Interaction between wind farms will be studied using the COSMO model;
  - Sensitivity tests will be conducted testing different conditions in the wind farms (e.g. switching off the upstream wind parks).
- WP 5: Optimal control of wind-farm clusters.
  - Assess whether optimal control of wind-farm clusters improves total yield or not using realistic wind-farm cluster layout;
  - Verify optimal control using the COSMO model.

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Methodology

ERA5 data

30km horizontal resolution

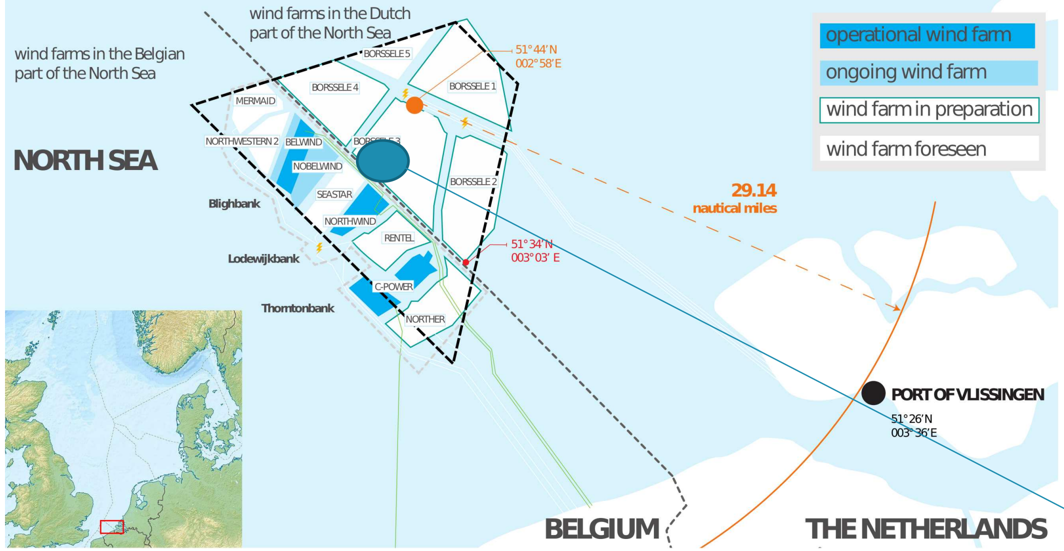
137 vertical levels

Why ERA 5?

- One of the best reanalysis available currently;
- High vertical resolution;
- Relatively high availability.

Data selection

- Year: 2016;
- One point extracted centered on the wind farm;



51.6N and 3E

[4]:Adapted from Allaerts et al. (2018).

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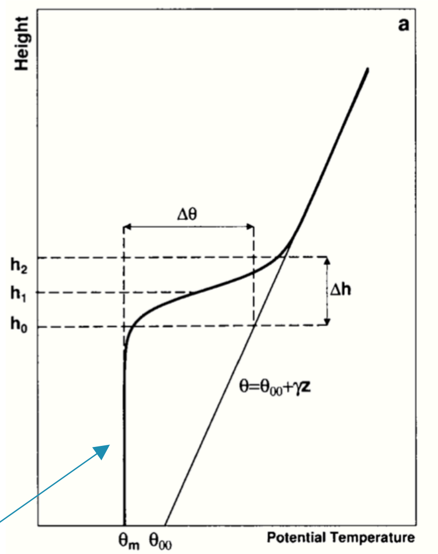
Methodology

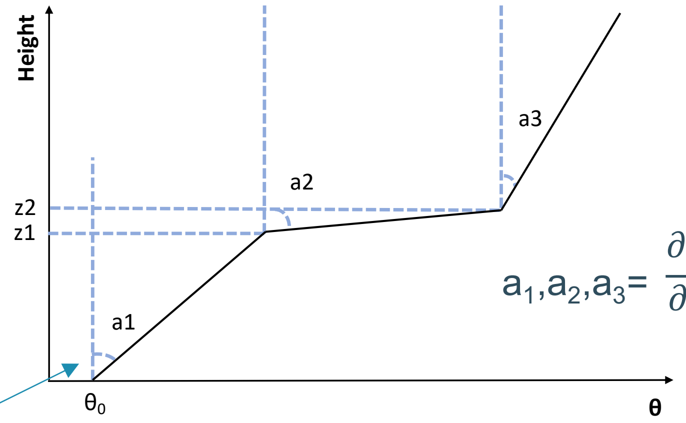
Old curve fit based on Rampanelli and Zardi (2004):



Always mixed boundary layer

Allows more freedom for the first layer (mixed, stable or unstable)

Piecewise linear regression:



$a_1, a_2, a_3 = \frac{\partial\theta}{\partial z} =$ Lapse rate

$$\theta(z) = \begin{cases} \theta_0 + a_1(z - z_1), & z_0 \leqslant z \leqslant z1 \\ \theta_0 + a_1(z - z_1) + a_2(z - z_2), & z_1 < z \leqslant z_2 \\ \ldots & \ldots \\ \theta_0 + a_1(z - z_1) + a_2(z - z_2) + \ldots + a_{\mathrm{nz}}(z - z_{\mathrm{nz\text{-}1}}), & z_{\mathrm{n\text{-}1}} < z \leqslant z_{\mathrm{n\text{-}1}} \end{cases}$$

Parameters extracted: a_1, a_2, a_3, z_1, z_2

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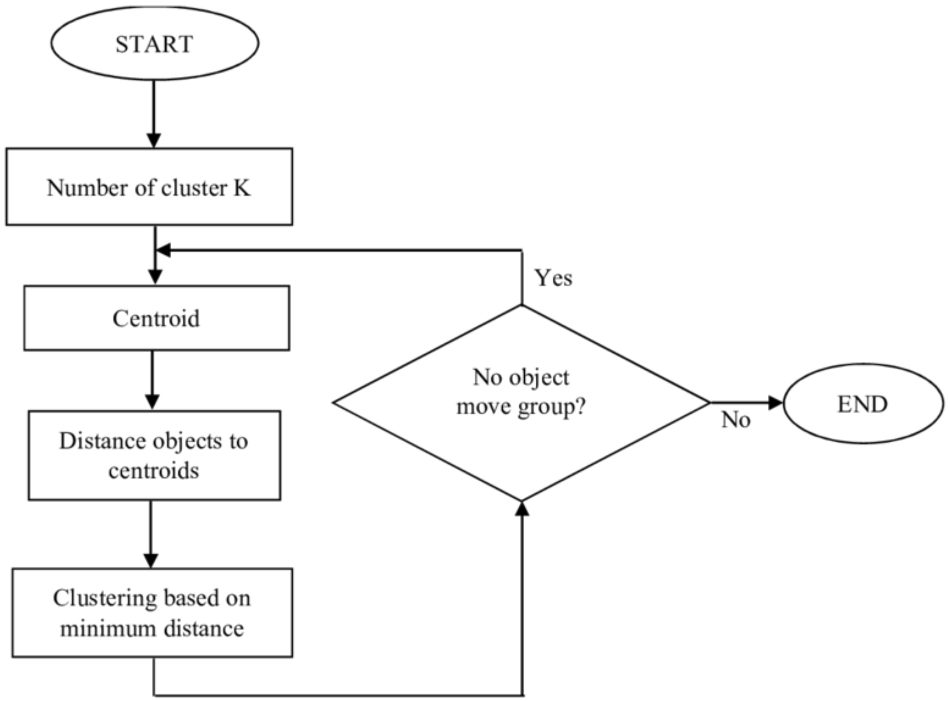
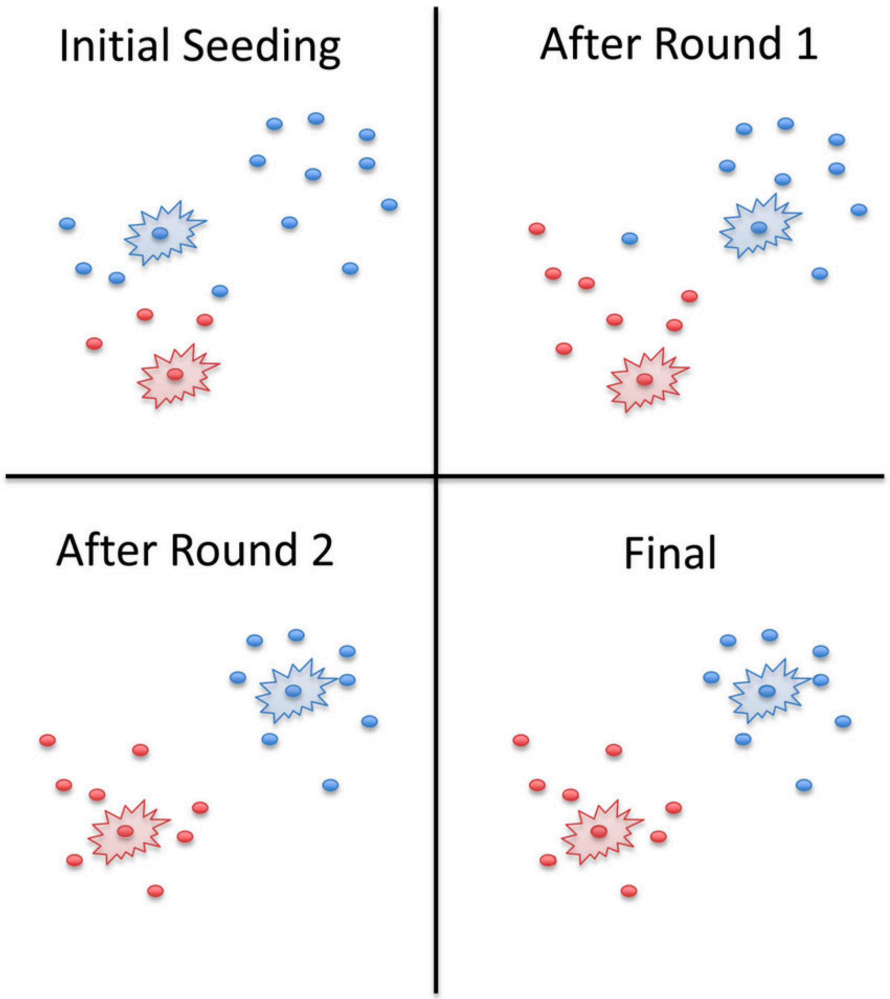
Methodology

K-means clustering:





[4]: Page et al. (2014).

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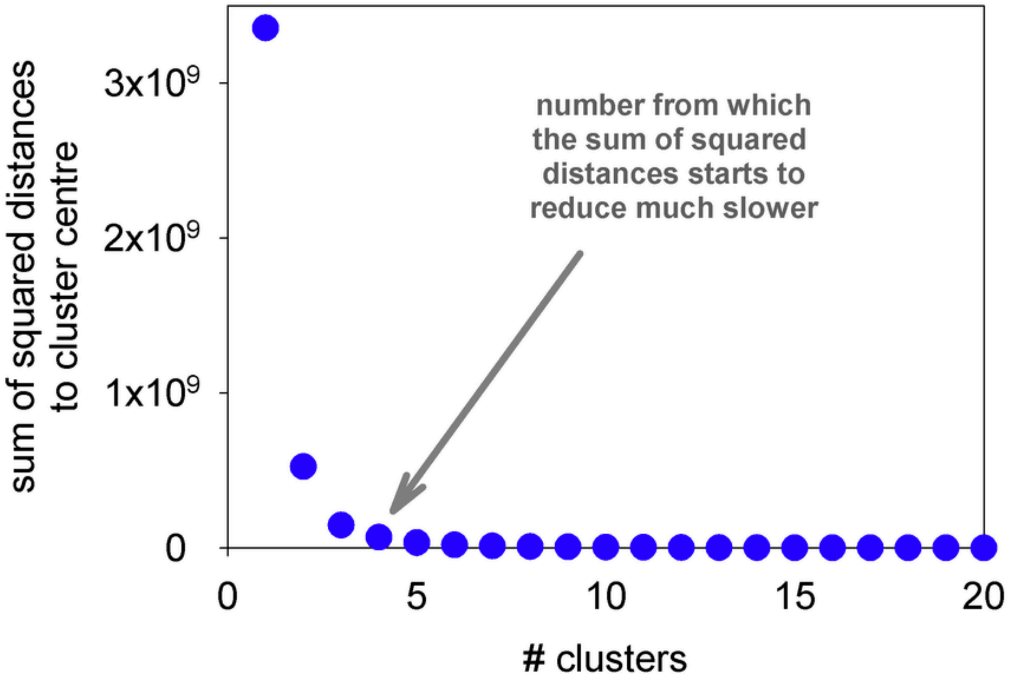
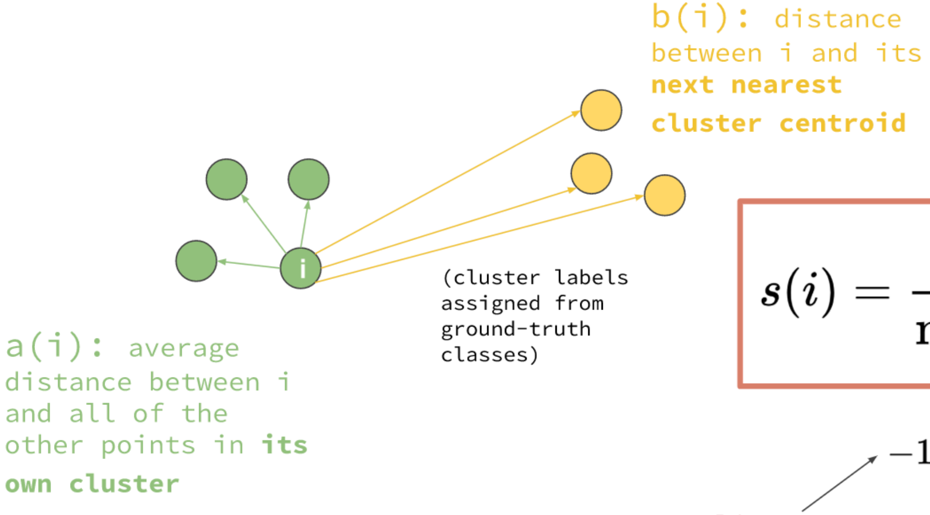
Choosing number of clusters

Elbow method:



Silhouette score:



For a single point, i

$$\boxed{s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}}}$$

$$-1 \leq s(i) \leq 1$$

Sprawling, overlapped clusters

Tight, well-separated clusters

[4]: Hartmann, A., Tom Gleeson, R. Rosolem, F. Pianosi, Y. Wada, and T. Wagener. "A large-scale simulation model to assess karstic groundwater recharge over Europe and the Mediterranean." (2015).

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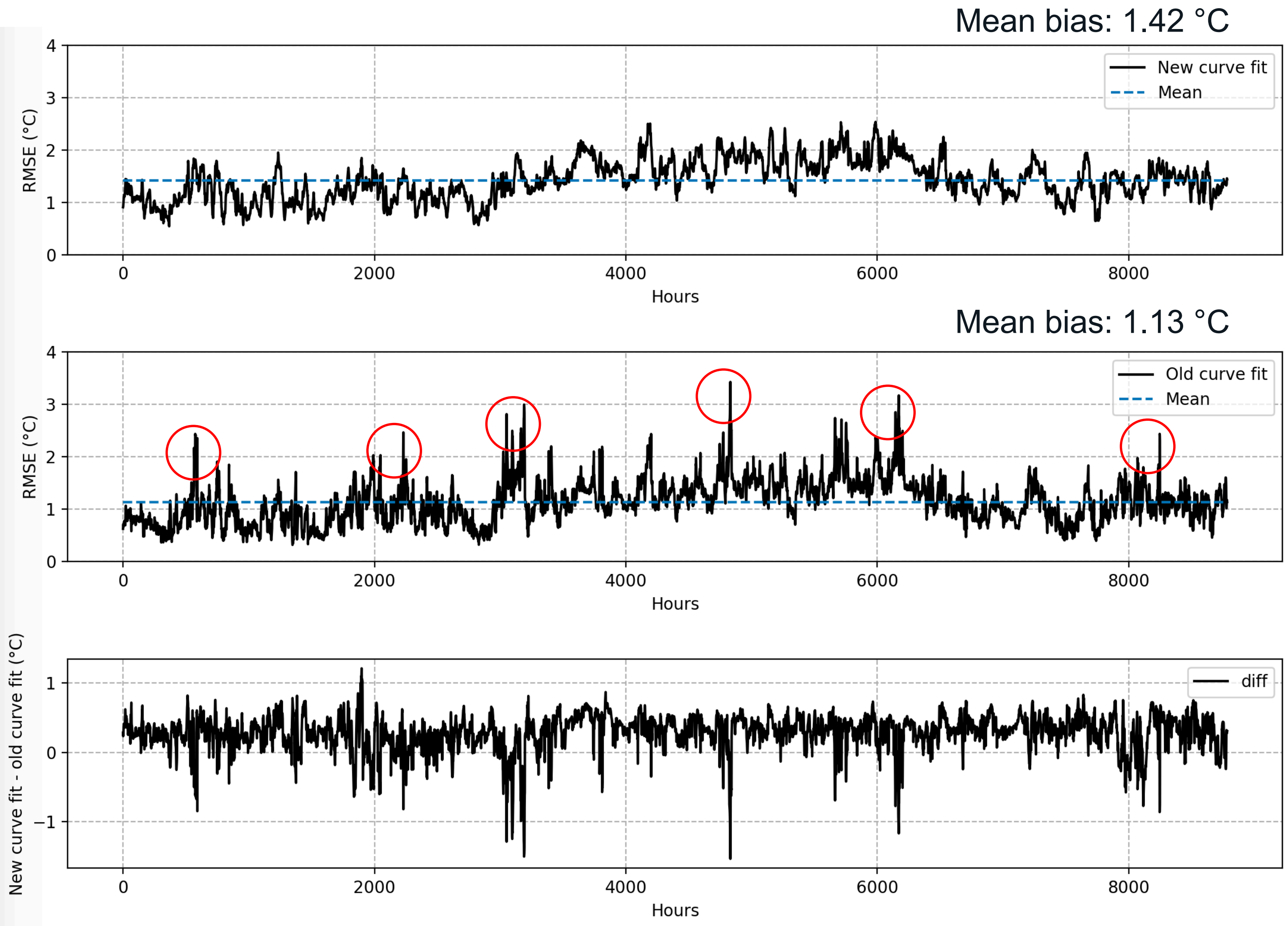
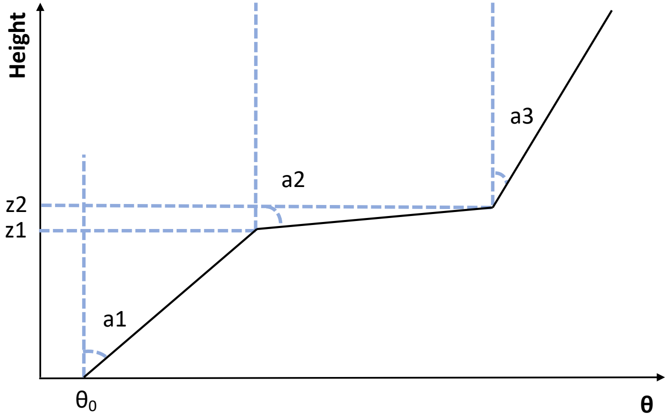
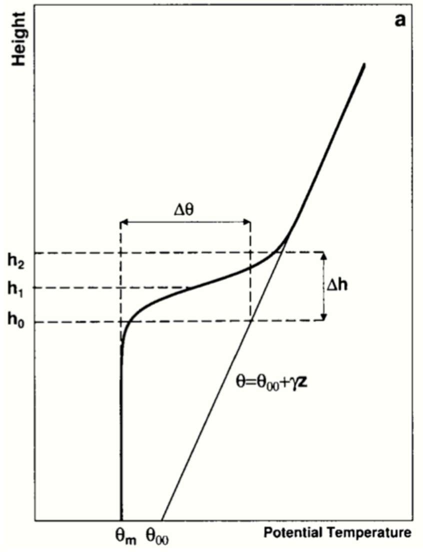
Validation

$$\mathrm{RMSE} = \sqrt{\sum \frac{(y_{pred} - y_{ref})^2}{N}}$$







Rampanelli & zardi

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K-means with quantile transform

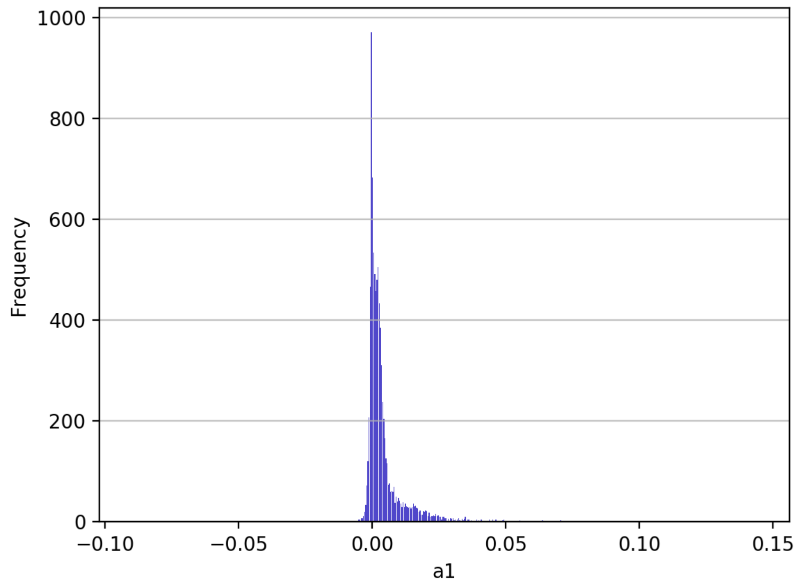
Quantile transformation

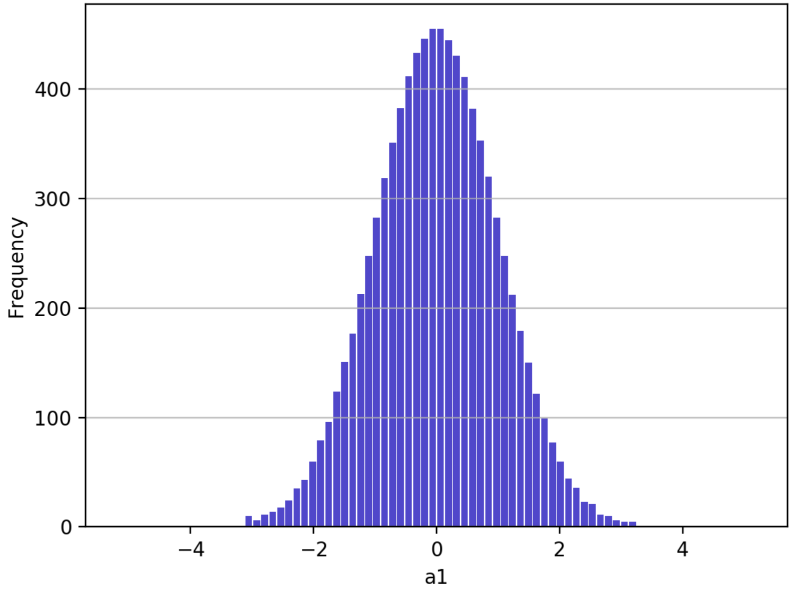
How does the quantile transformation work?

- The transformation is applied on each feature independently
- The cumulative density function of a feature is used to project the original values
- Features values of new/unseen data that fall **below** or **above** the fitted range is **mapped to the bounds** of the output distribution.

$$y_i = \Phi^{-1}(F(xi))$$

where F and Φ represent the CDFs of an empirical and standard Normal distribution, respectively.





[4]: Allaerts & Meyers, *J. Fluid Mech. (2019)*

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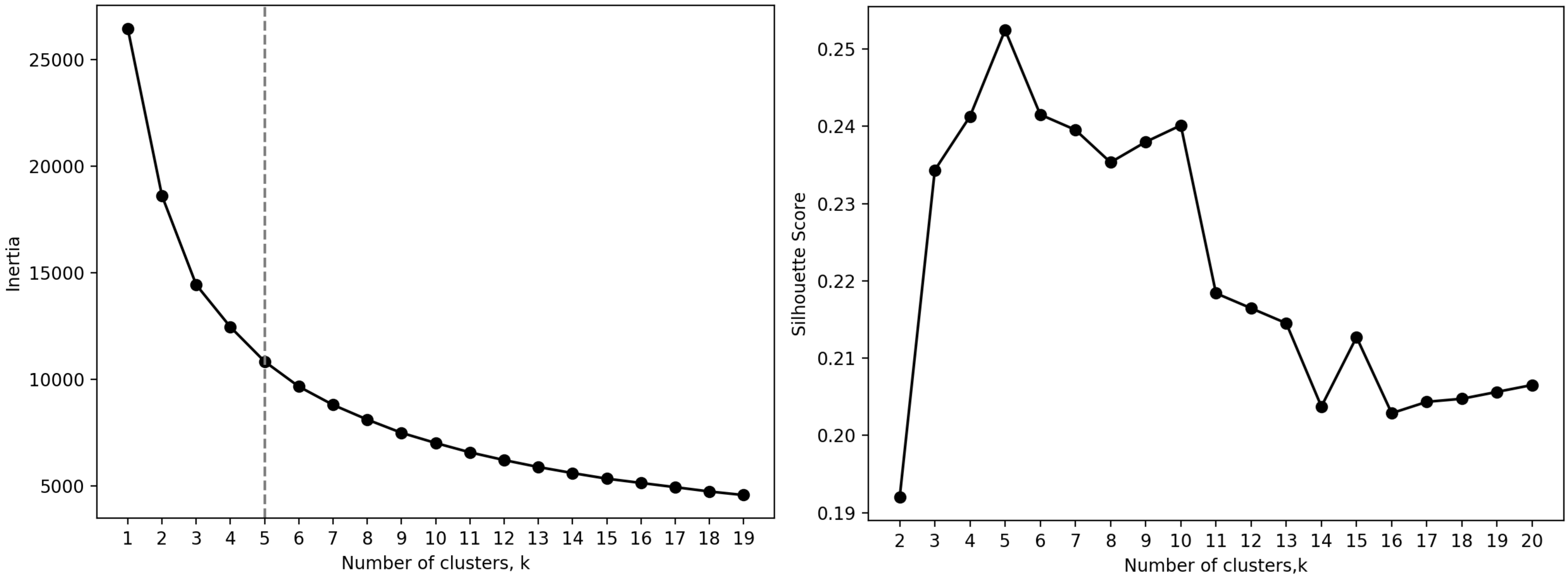
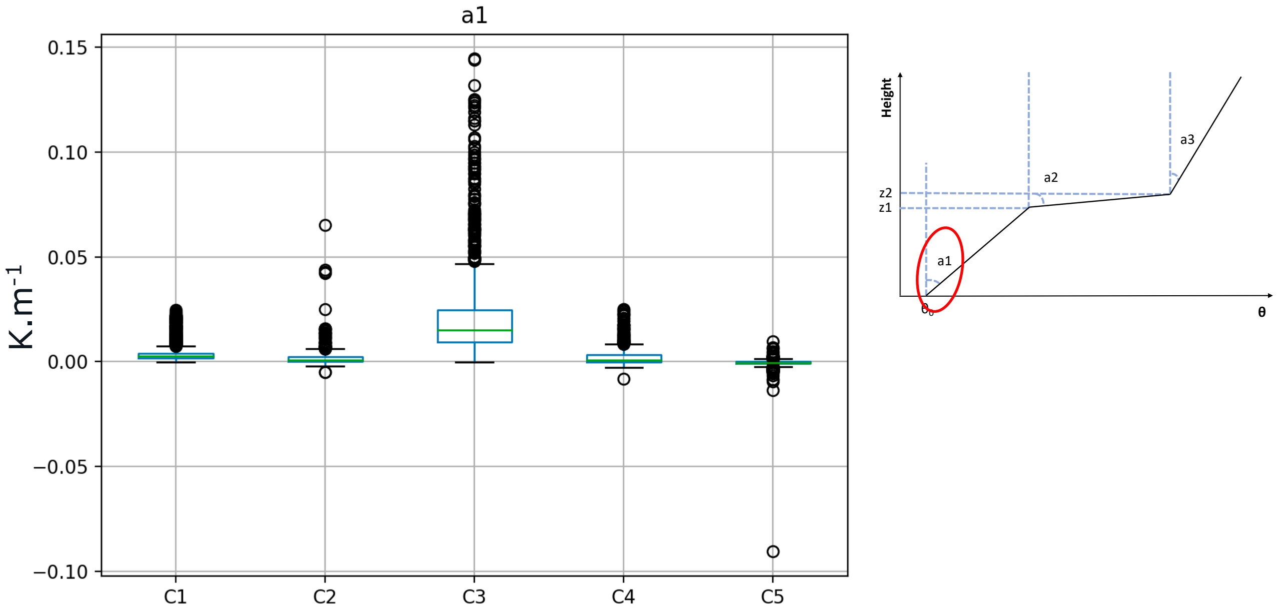
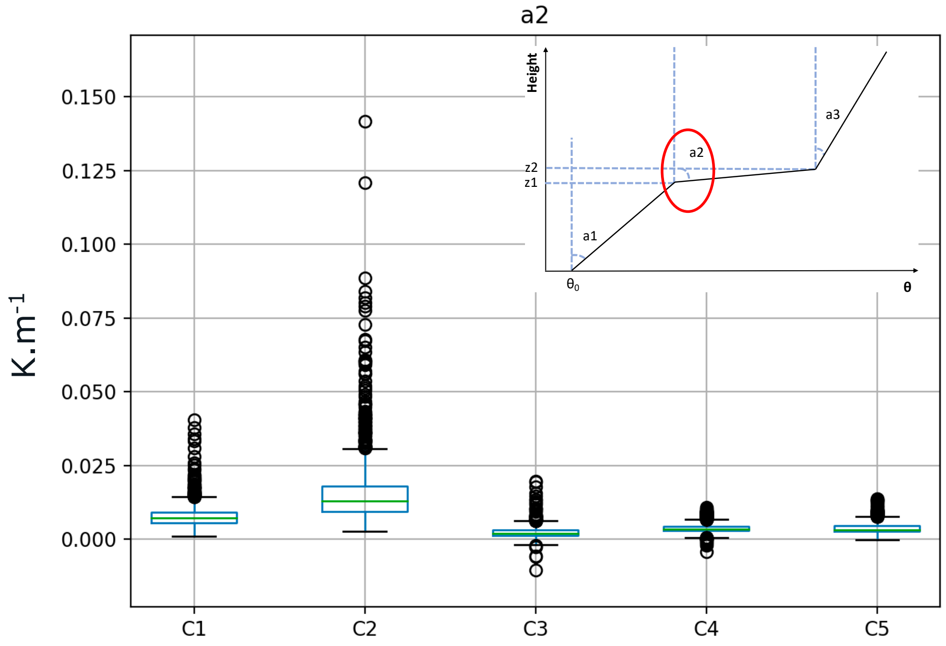
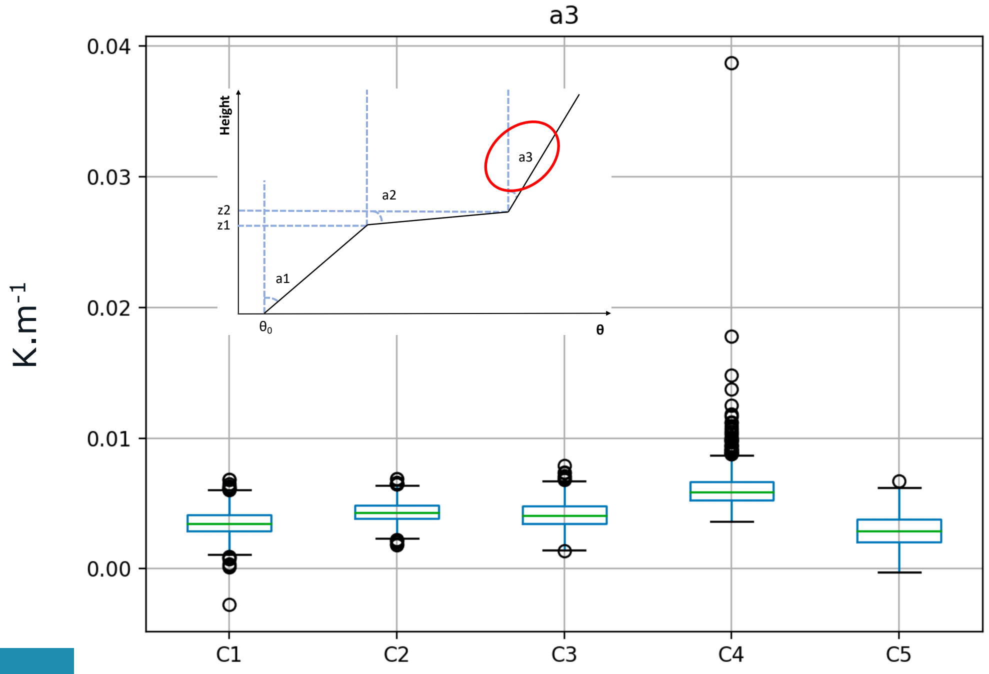

25000
20000
15000
10000
5000
Inertia
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Number of clusters, k
0.25
0.24
0.23
0.22
0.21
0.20
0.19
Silhouette Score
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Number of clusters,k


a1
K.m-1
0.15
0.10
0.05
0.00
−0.05
−0.10
C1
C2
C3
C4
C5
Height
z2
z1
a1
a2
a3
θ0
θ


a2
K.m-1
0.150
0.125
0.100
0.075
0.050
0.025
0.000
C1
C2
C3
C4
C5
Height
z2
z1
a1
a2
a3
θ0
θ


a3
K.m-1
0.04
0.03
0.02
0.01
0.00
C1
C2
C3
C4
C5
Height
z2
z1
a1
a2
a3
θ0
θ

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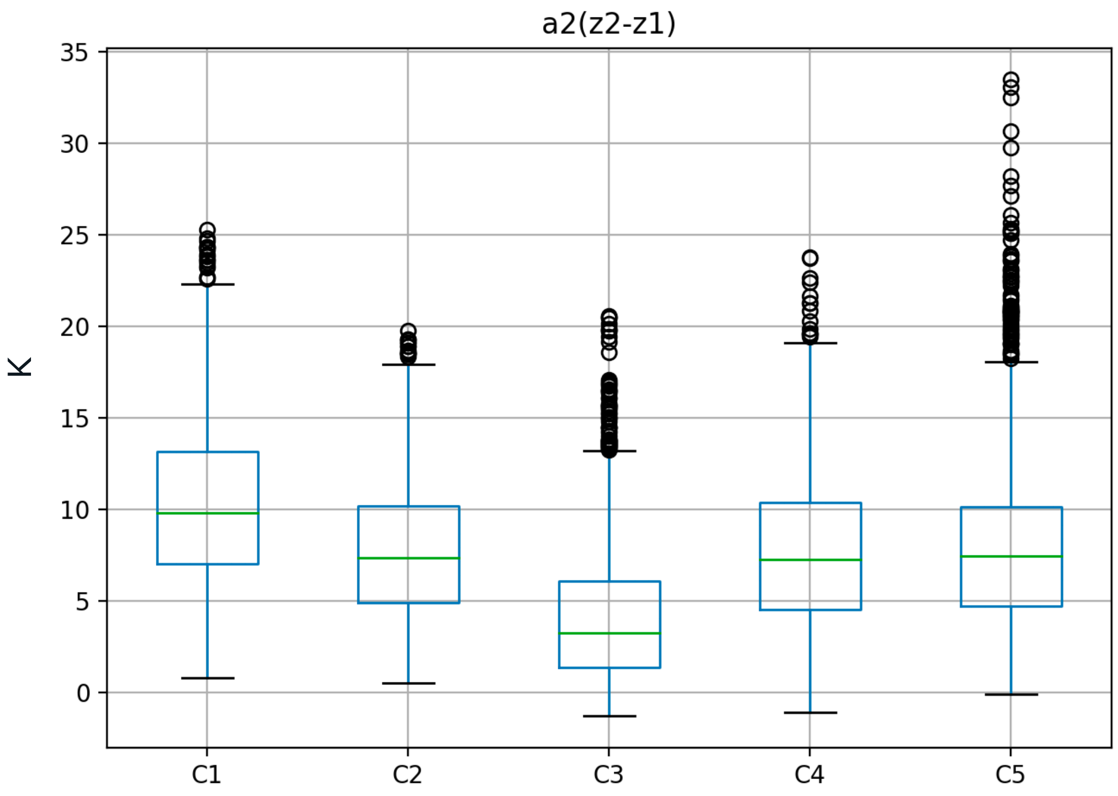
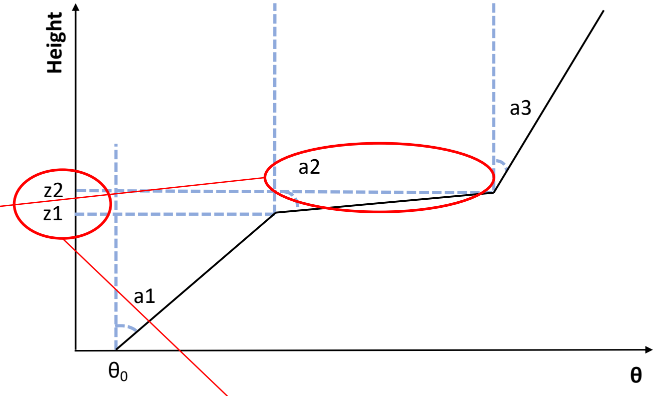
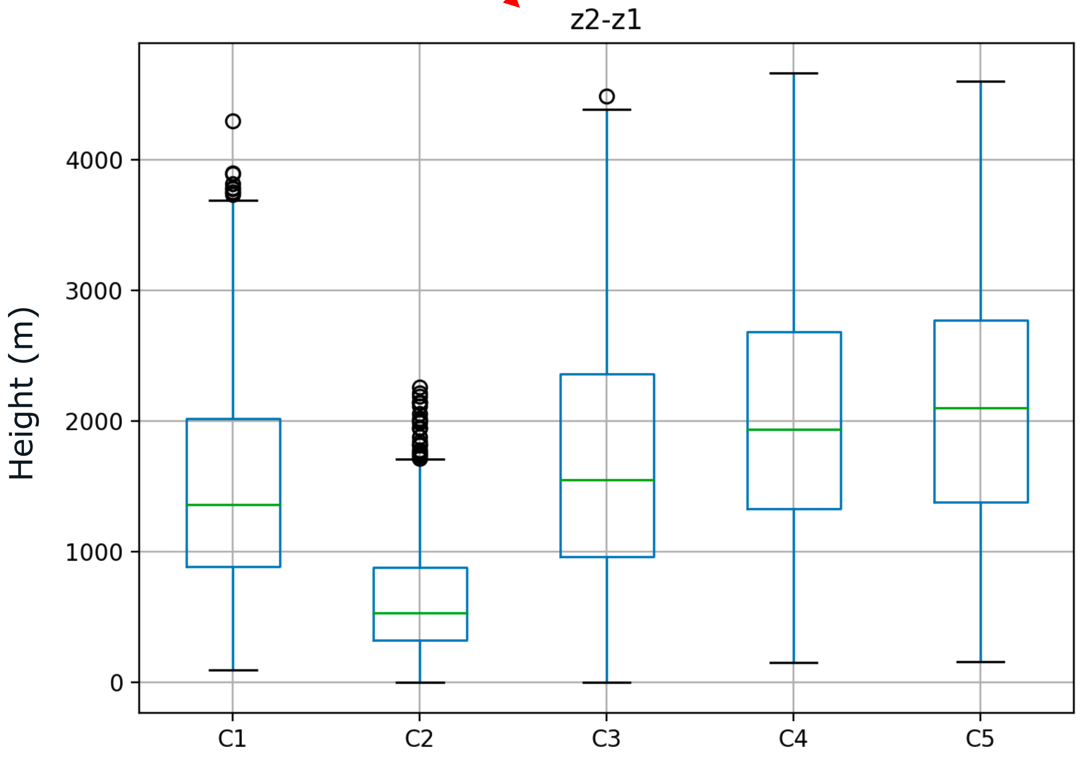
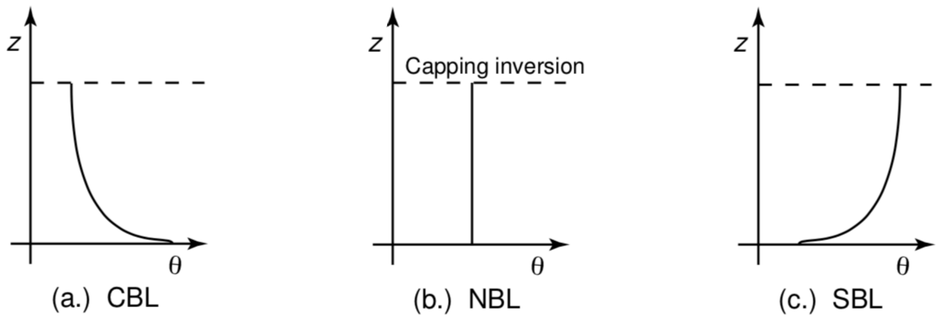
Inversion strength

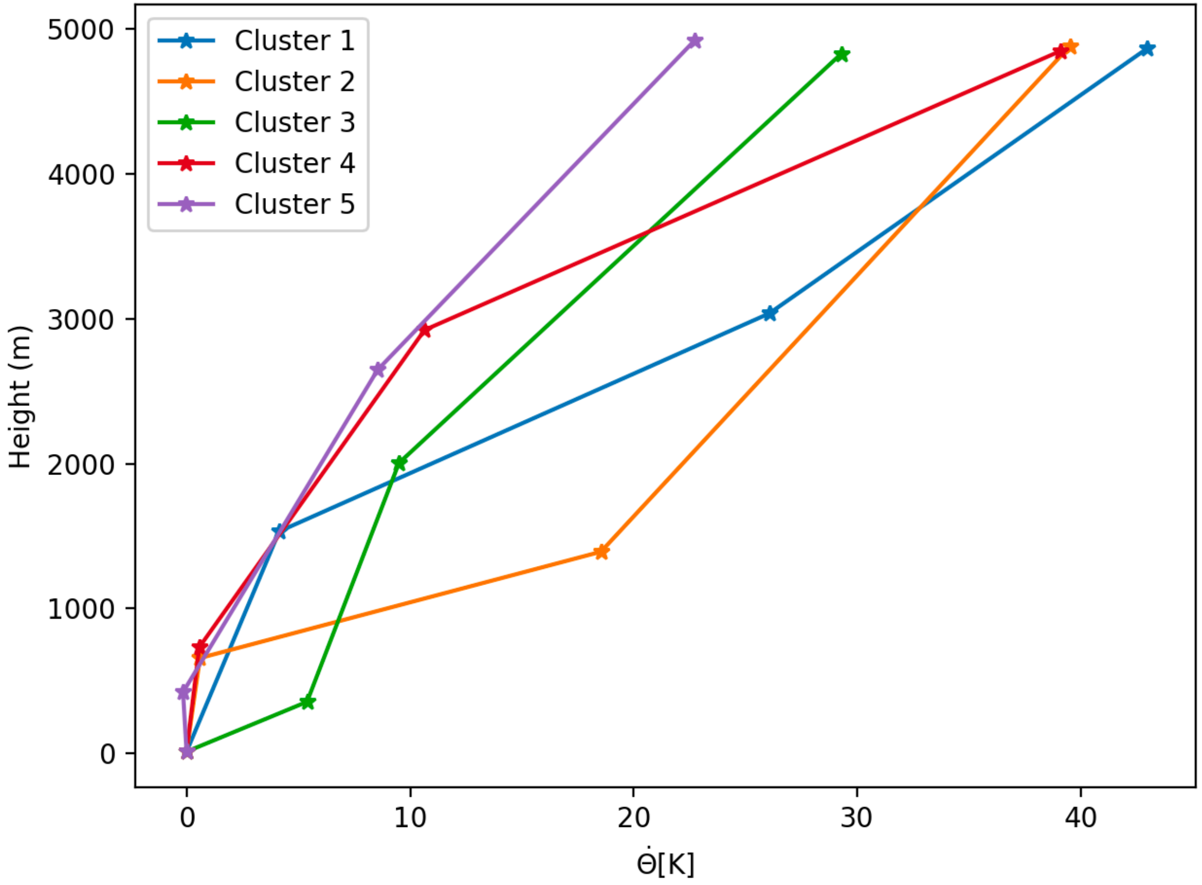








	BLH	BL condition	Capping inversion?	Free atm
Cluster 1	Very deep	Stable	No	Strong LR
Cluster 2	Shallow	Neutral	Yes	Strong LR
Cluster 3	Very shallow	Super stable	Residual layer	Moderate LR
Cluster 4	Shallow	Neutral	No	Super strong LR
Cluster 5	Very shallow	Unstable	No	Weak LR



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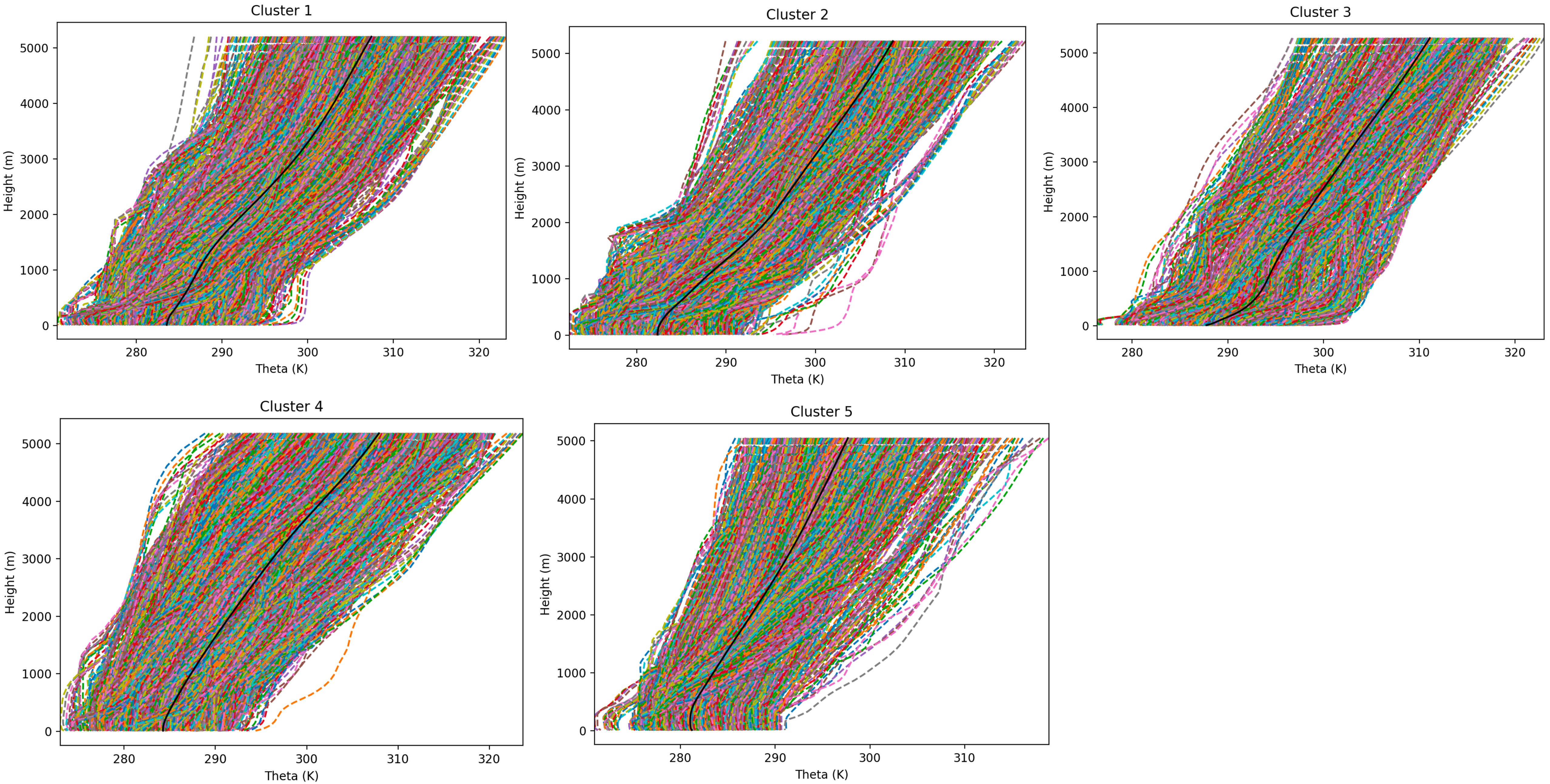
Cluster 1
Cluster 2
Cluster 3
Cluster 4
Cluster 5
Height (m)
Theta (K)
0
1000
2000
3000
4000
5000
280
290
300
310
320

K-means with outlier removal

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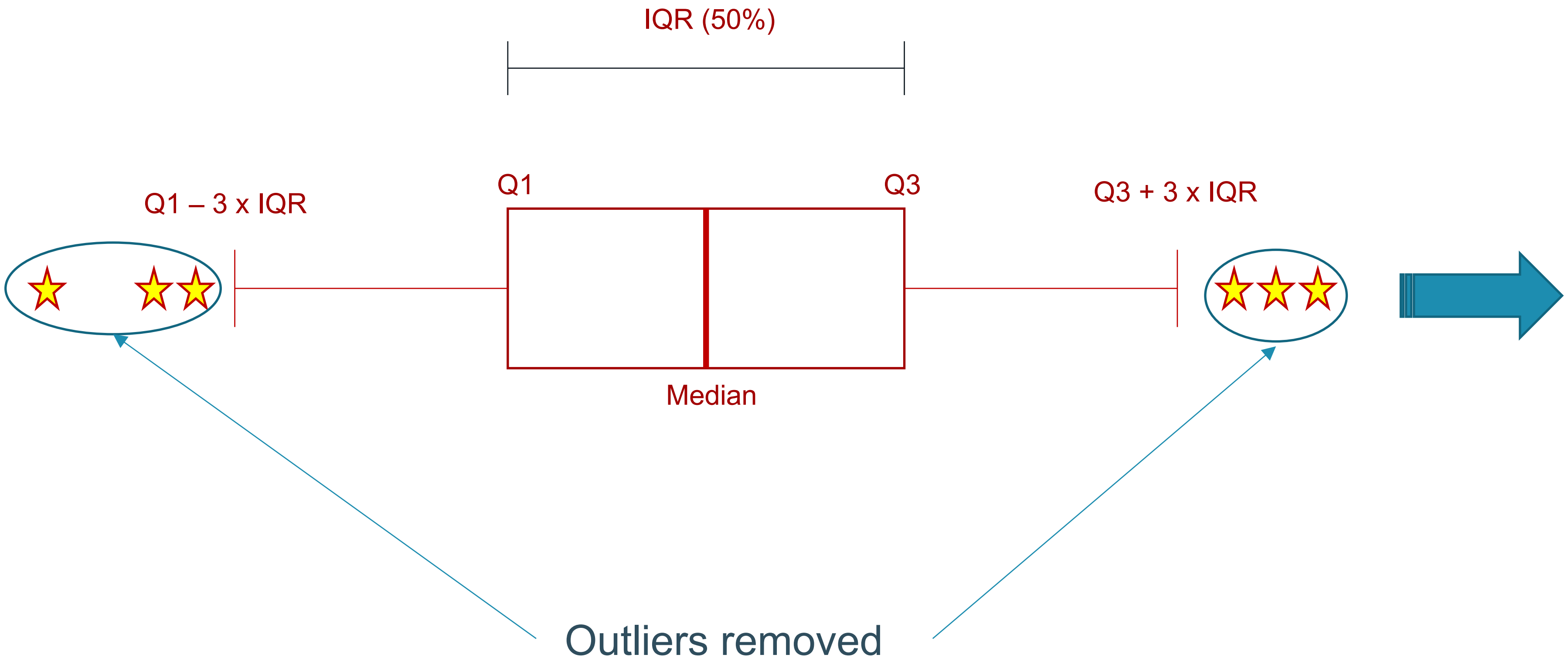
Data Original: 8784h
After outlier removal: 8000h (8.93% of the data removed)

- Applied for each of the features (a_1,a_2,a_3,z_1,z_2)



$$x_{scaled} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

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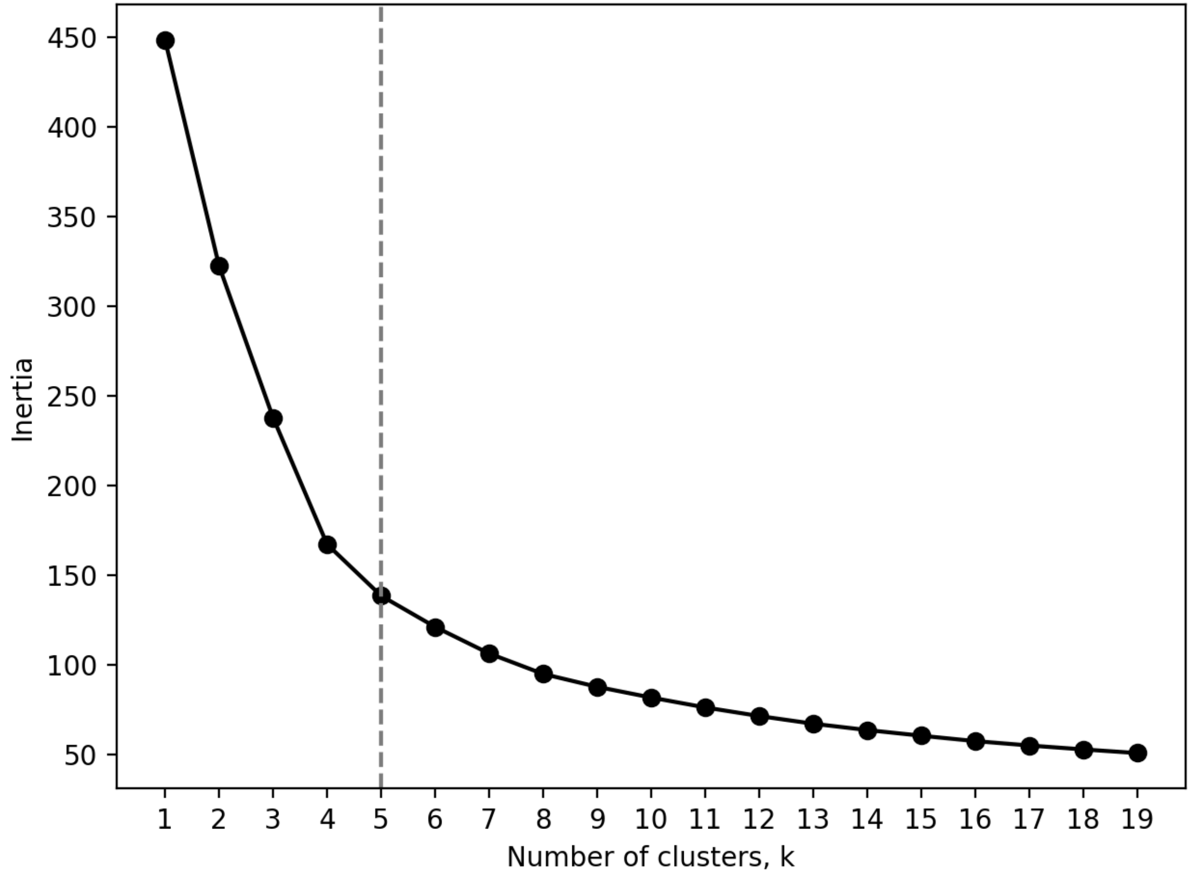
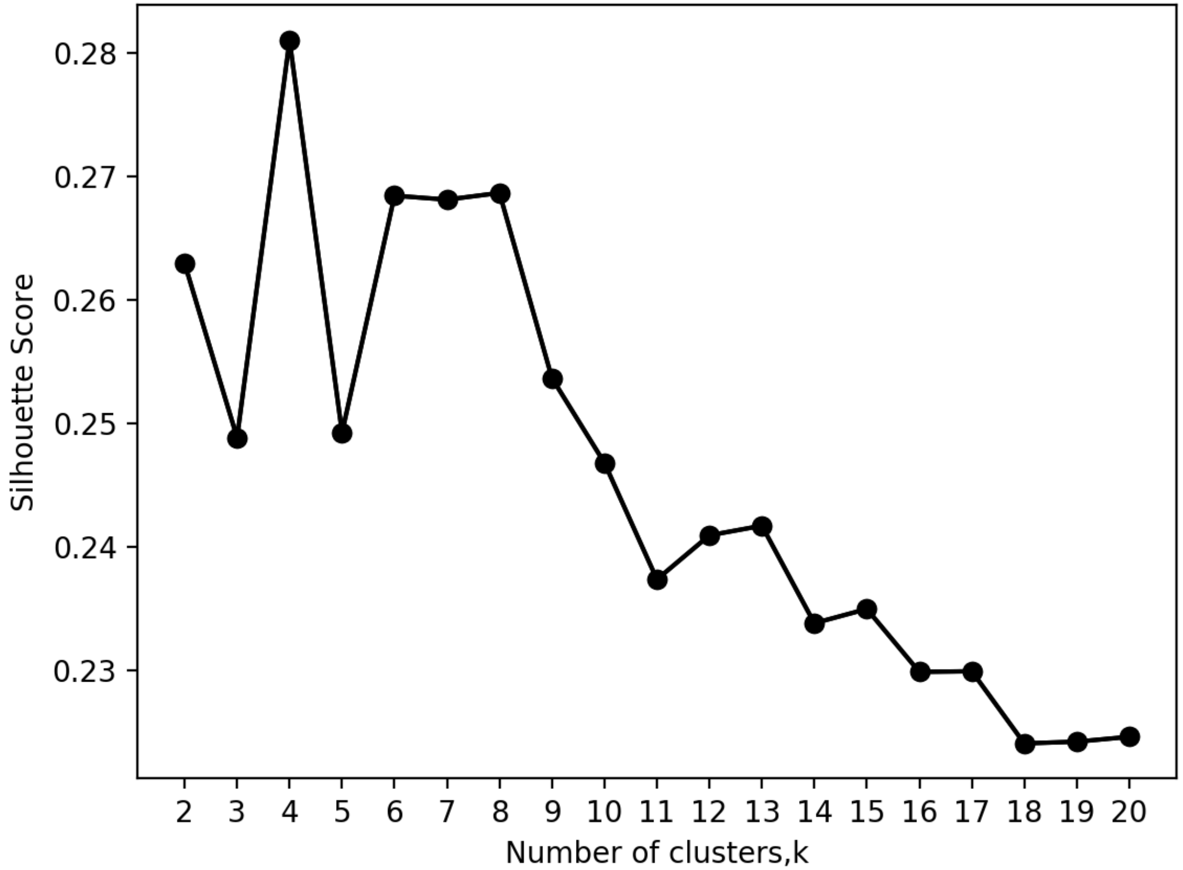
Data Original: 8784h
After outlier removal: 8000h (8.93% of the data removed)

- To maintain consistence with the previous analysis, we chose 5 clusters.





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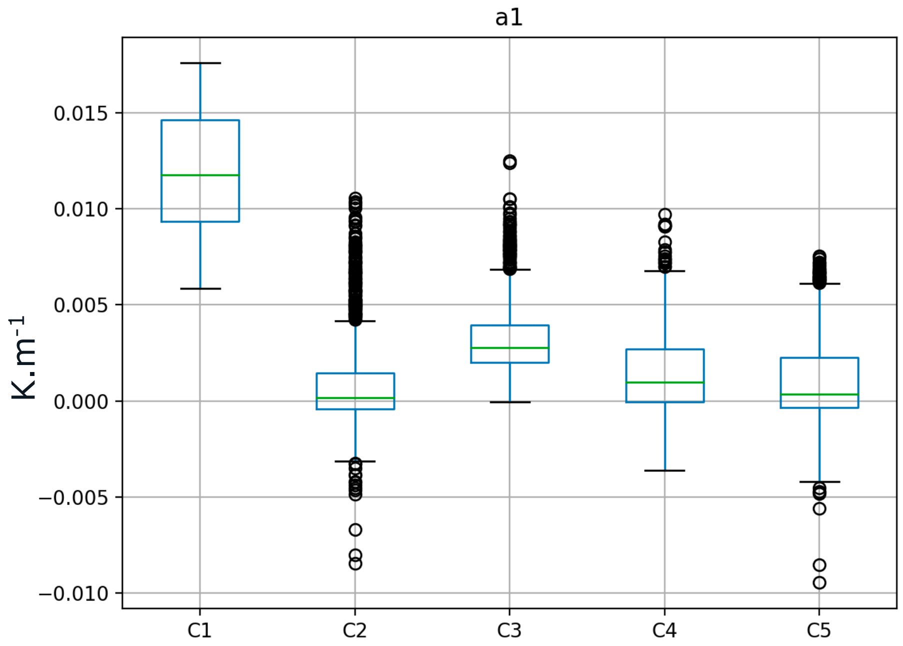
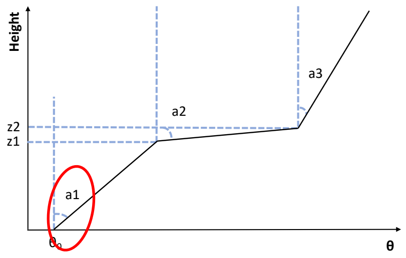
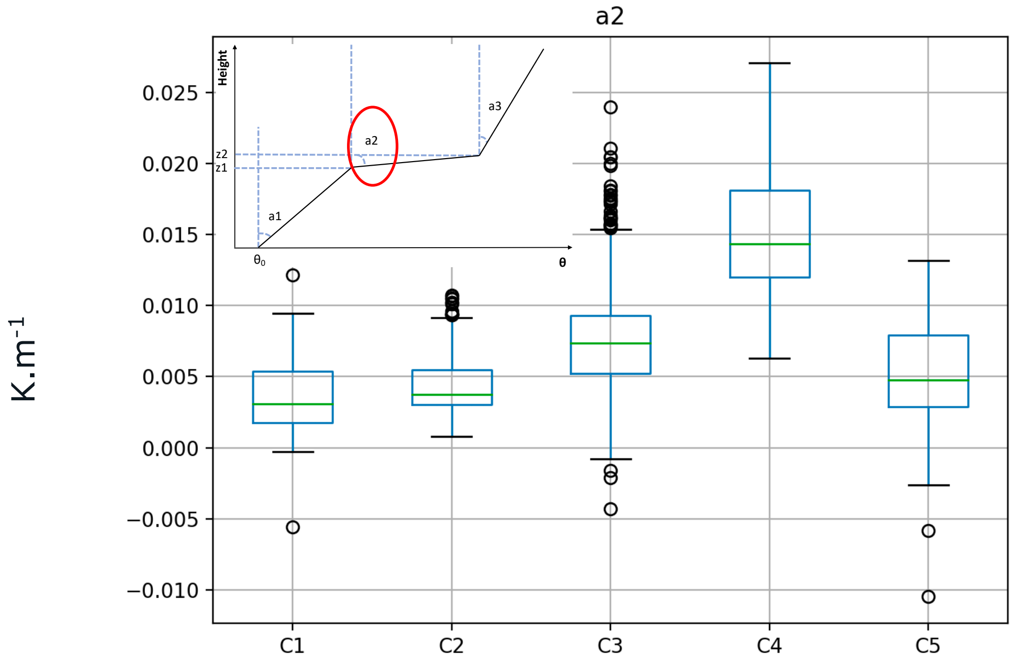
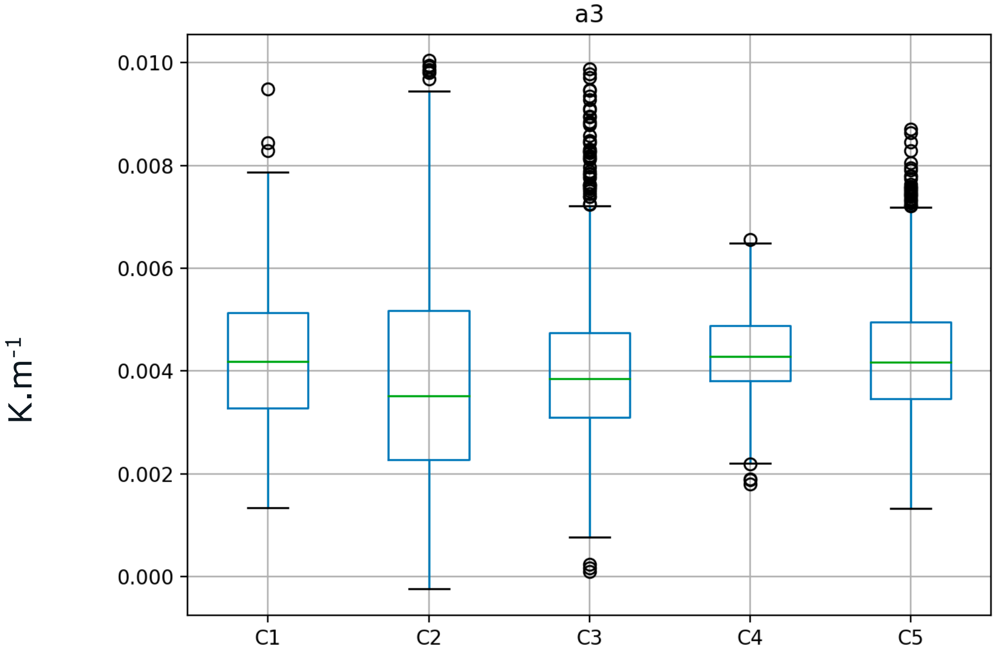
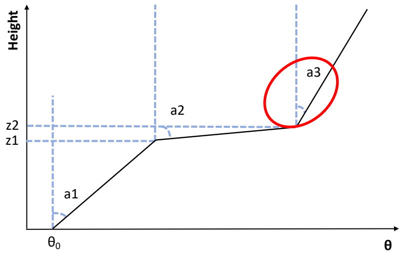

a1
K.m-1
0.015
0.010
0.005
0.000
−0.005
−0.010
C1
C2
C3
C4
C5

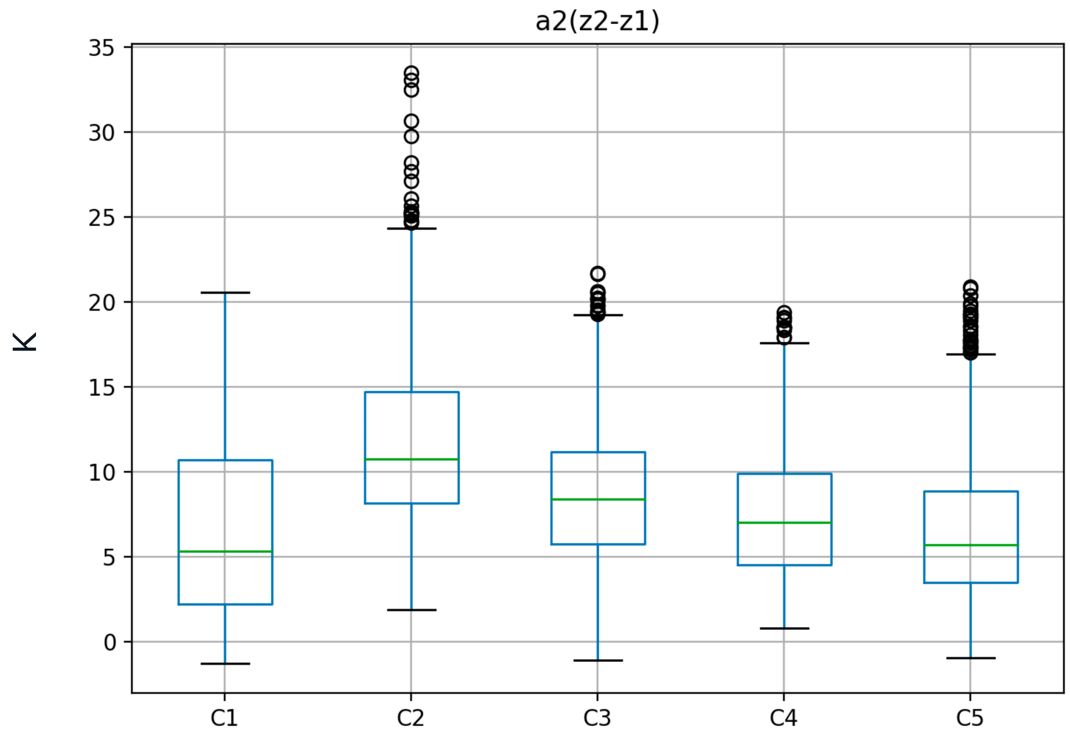

Height
z2
z1
a1
a2
a3
θ0
θ

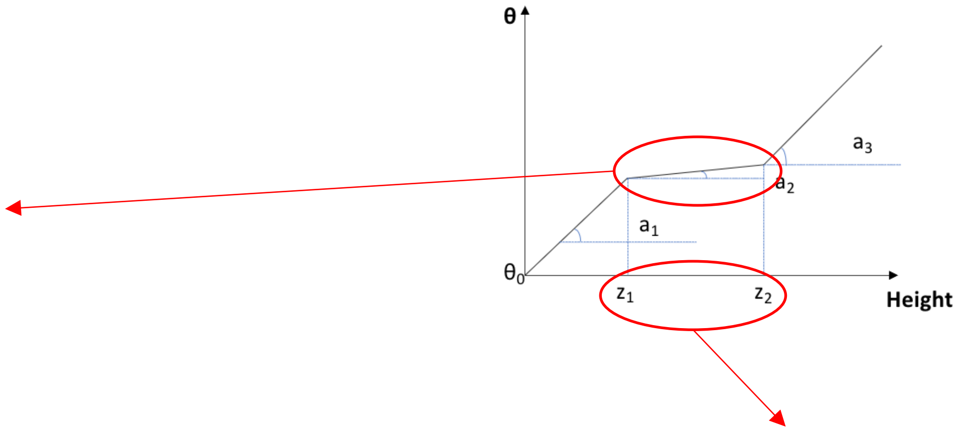

a2
K.m-1
0.025
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
C1
C2
C3
C4
C5
Height
z2
z1
a1
a2
a3
θ0
θ

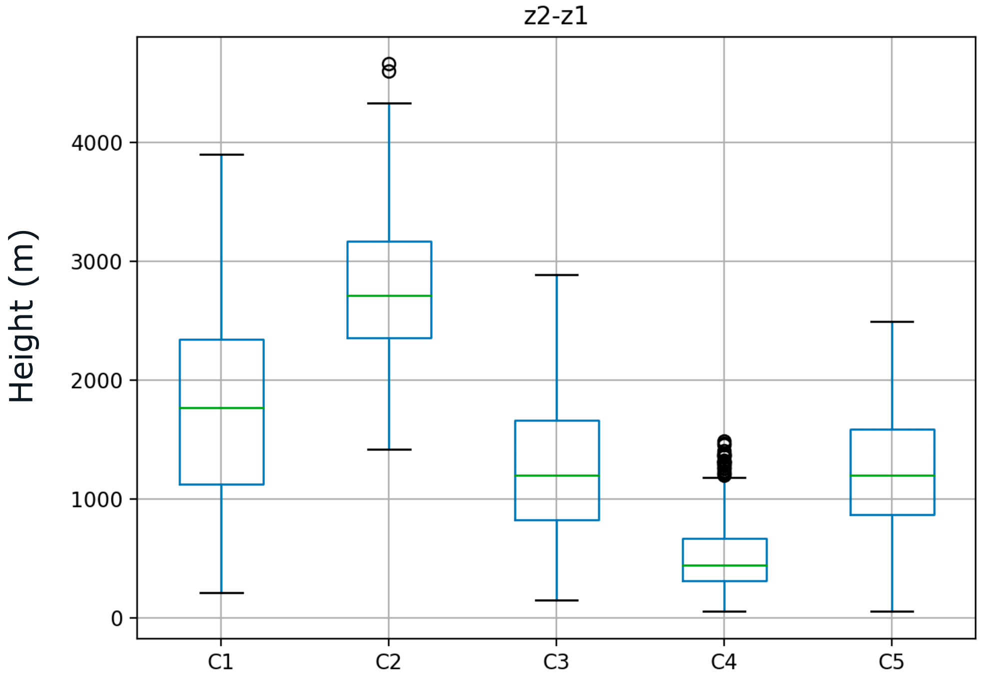

a3
K.m-1
0.010
0.008
0.006
0.004
0.002
0.000
C1
C2
C3
C4
C5


Height
z2
z1
a1
a2
a3
θ0
θ

Inversion strength







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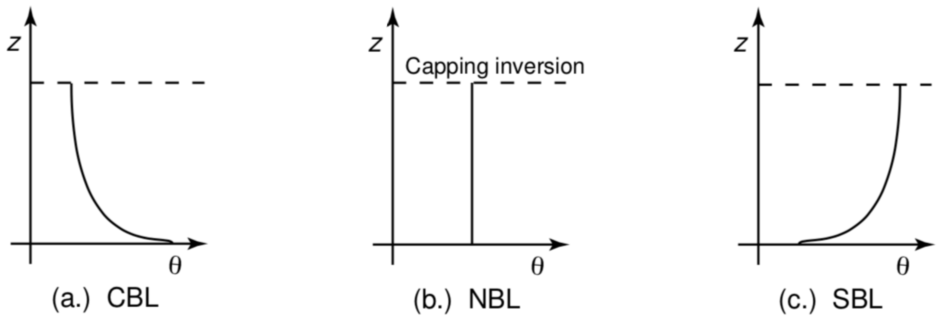
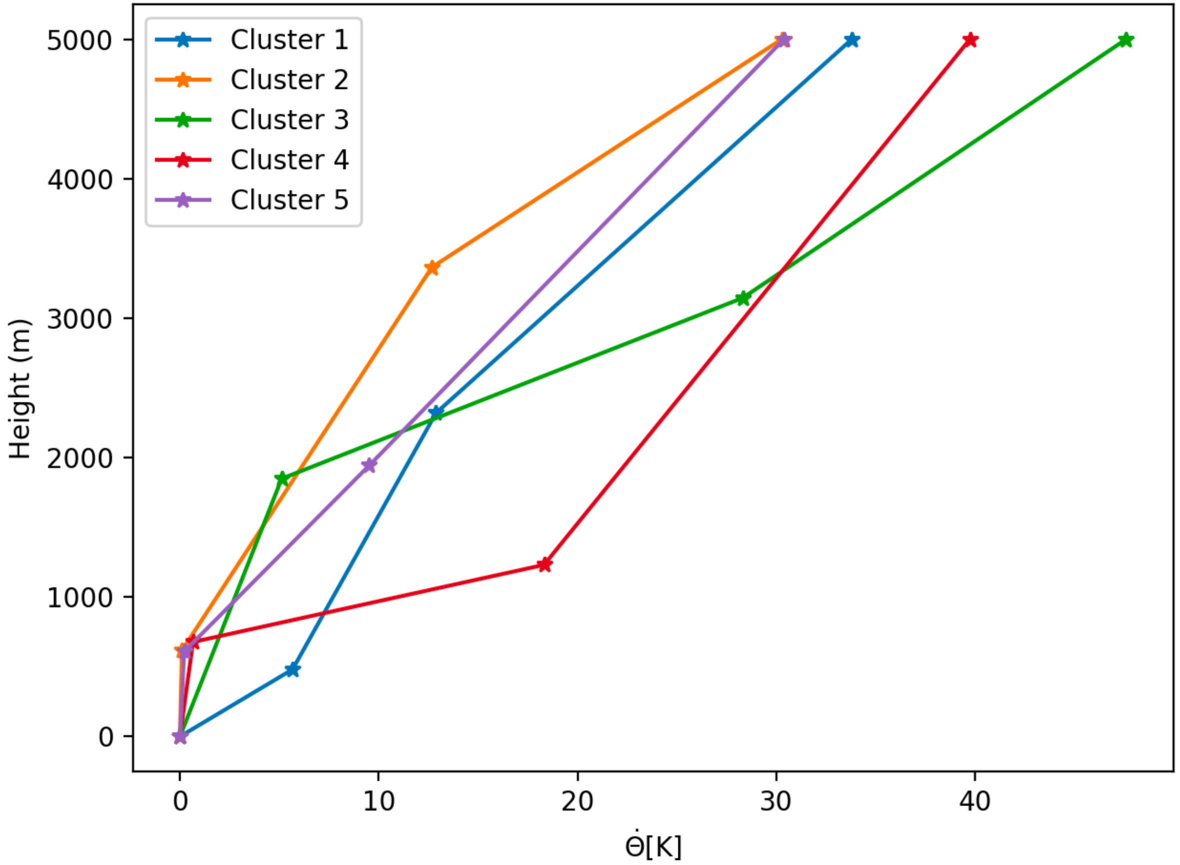
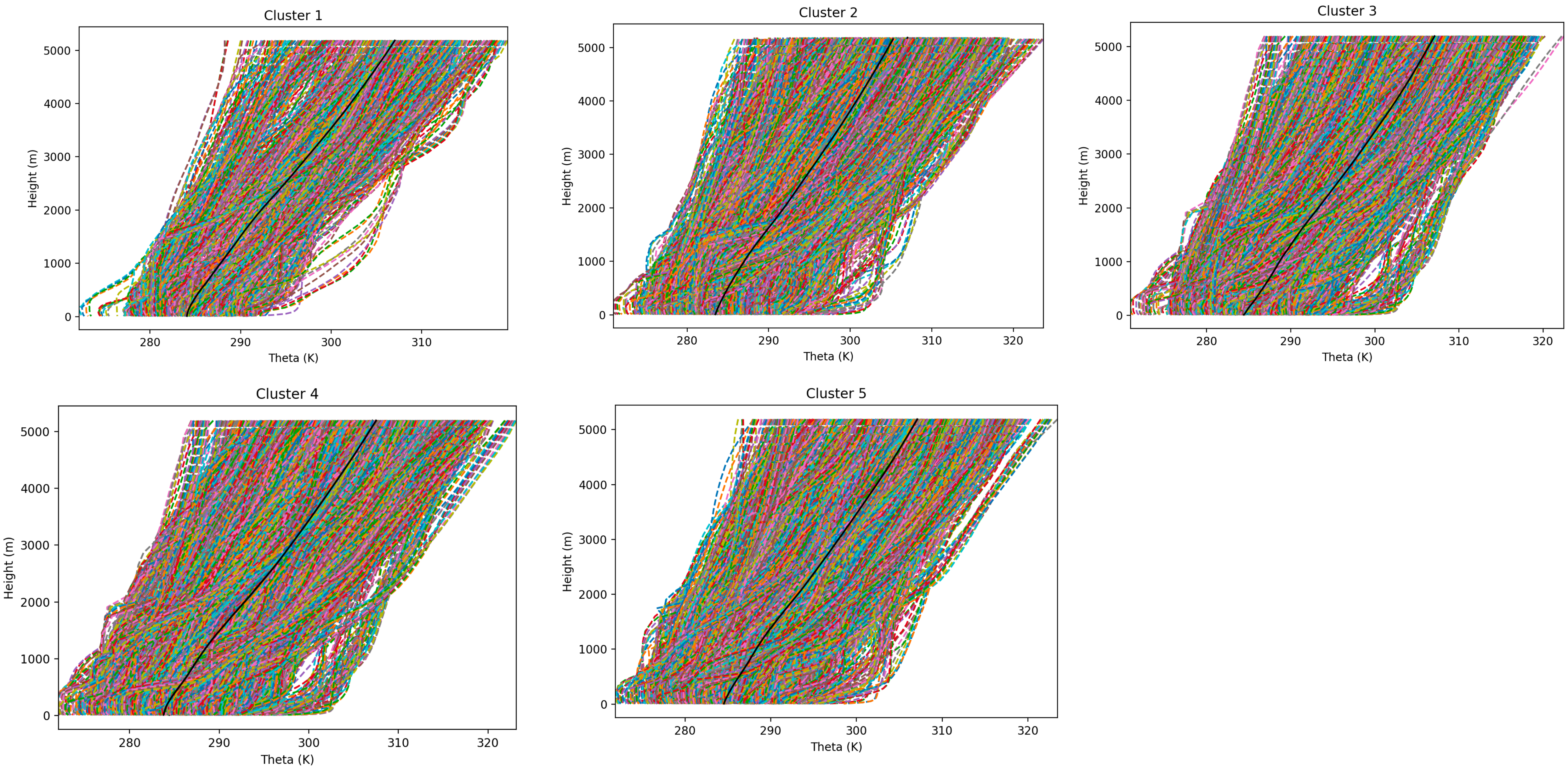


	BLH	BL condition	Capping inversion?	Free atm
Cluster 1	Very shallow	Super stable	Residual layer	Strong LR
Cluster 2	Shallow	Neutral	No	Strong LR
Cluster 3	Deep	Stable	No	Strong LR
Cluster 4	Shallow	Neutral	Yes	Super strong LR
Cluster 5	Shallow	Neutral	No	Strong LR




Cluster 1
Cluster 2
Cluster 3
Cluster 4
Cluster 5
Height (m)
Theta (K)
0
1000
2000
3000
4000
5000
280
290
300
310
320

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Conclusion & Future work

Conclusions

- The clustering algorithm still does not separate all the cases well.
- Perhaps, the number of lines for the temperature does not capture most of the patterns.

Future work

- Investigate how many cases a capping inversion happens.
- Apply a different clustering algorithm that is not heavily influenced by outliers.
- Try to add wind (speed and direction) in the classification.

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     - Research plan
  2. Current focus:
     - Methodology
     - Results
       - Quantile transform
       - Outlier removal
  3. Conclusion and future work

- Education:

  1. Papers
  2. Attended courses
  3. Conferences
  4. Courses to be followed

KU LEUVEN

Education

1. Papers:

- Local circulations features in the Eastern Amazon: High-resolution simulations (**accepted**)
- Disentangling the Local Circulations over a Region with Complex Physiography in the Eastern Amazon: A Modeling Approach (**submitted**).

2. Attended courses:

- Atmospheric modelling (6 ECTS);
- Modelling land use changes (6 ECTS);

3. Conferences:

- COSMO-CLM numerical modelling training course (Langen, Germany 08-12 April 2019)

Education

4. Courses to be followed (blueprint):

- Academic English: Writing skills (2 ECTS);
- Research seminars in geography (3 ECTS)
- Advanced geography (3 ECTS)
- Science communication and outreach (6 ECTS)

5. Contribution to education:

- Submitted proposal for master’s thesis: Assessing wind resources changes over the North Sea from global climate models.
- Introduction to geoprocessing (3 ECTS second semester)

Thank you for your attention!

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