OpenTURNS User Day #16

23 March 2023

Modeling the impact of atmospheric variables on the performance of an aircraft during take-off: *Towards the adaptation of air traffic operations to global warming*

PhD student: Suzanne Salles[1][2]

Directors: Sophie Ricci[1], Nicolas Gourdain[2]

[1] *CECI, CERFACS/UMR5318 CNRS*

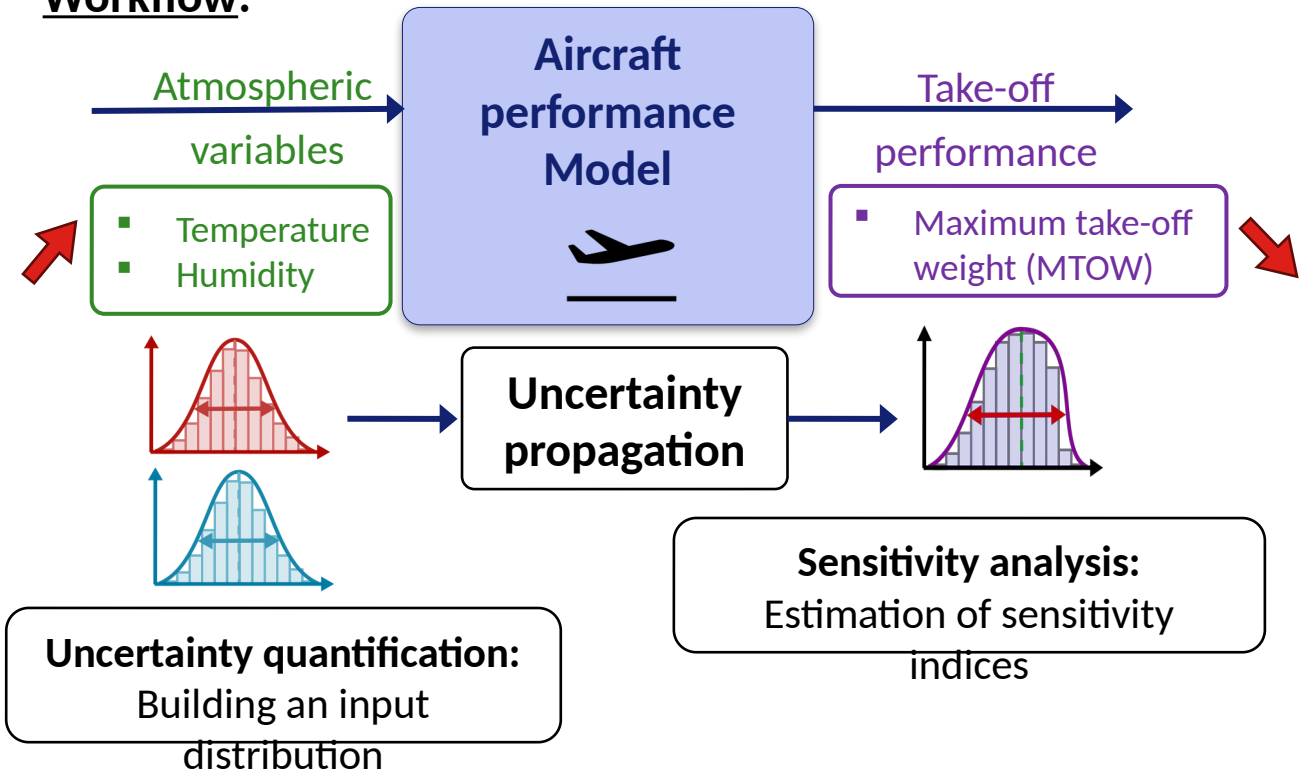
[2] *DAEP, ISAE-SUPAERO, Univ. of Toulouse*

Introduction

Context of the study

How will atmospheric changes due to climate change affect aircraft performance during take-off in the future?

Workflow:



- Quantify the influence of atmospheric input variables on aircraft performance output
- Quantify the sensitivity of performance to these variables

Input data

Variables

- **Huss**: Daily mean specific humidity
- **Tasmax**: Daily maximum temperature (K)

Specific humidity:

mass of water vapor

total mass of the air parcel

Future period:

➢ 2015-2100 (In this presentation: **2020-2050**)

Localization:

➢ Database of 13 airports around the world

4 different SSP (Shared Socio-economic Pathways) scenarios:

➢ SSP1-2.6, SSP2-4.5, **SSP3-7.0**, and SSP5-8.5

Outputs of climate model: CNRM-CM6-1

➢ Fully coupled atmosphere-ocean general circulation model

➢ Developed by the CNRM/CERFACS modelling group for CMIP6 project [4]

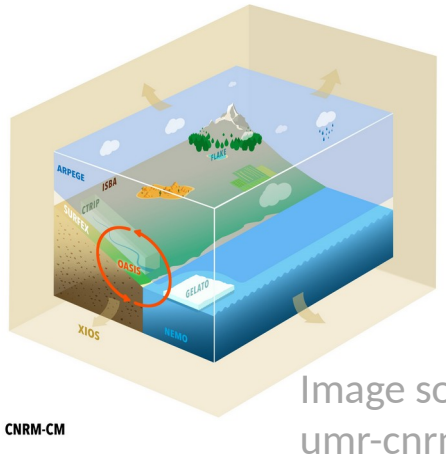
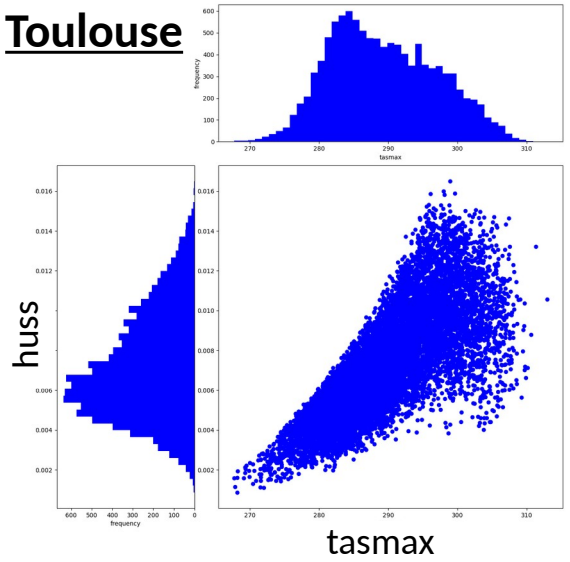


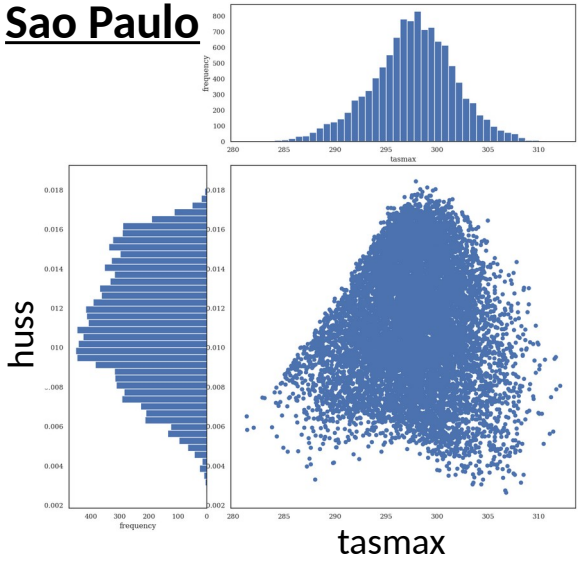
Image source: umr-cnrm

What the data looks like

Toulouse



Sao Paulo

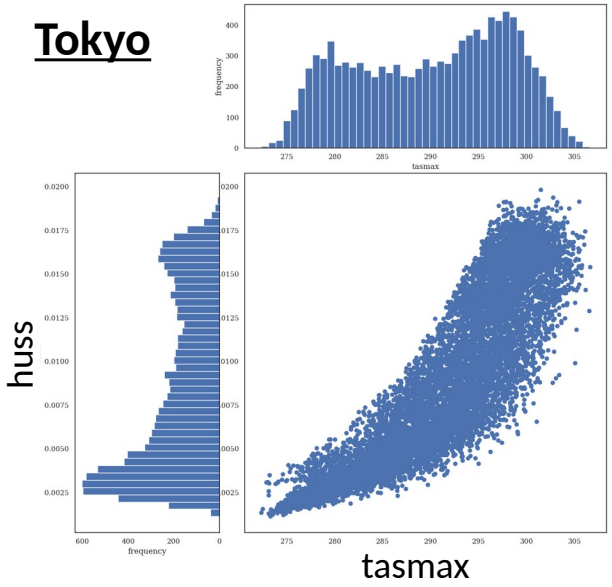


In the values space

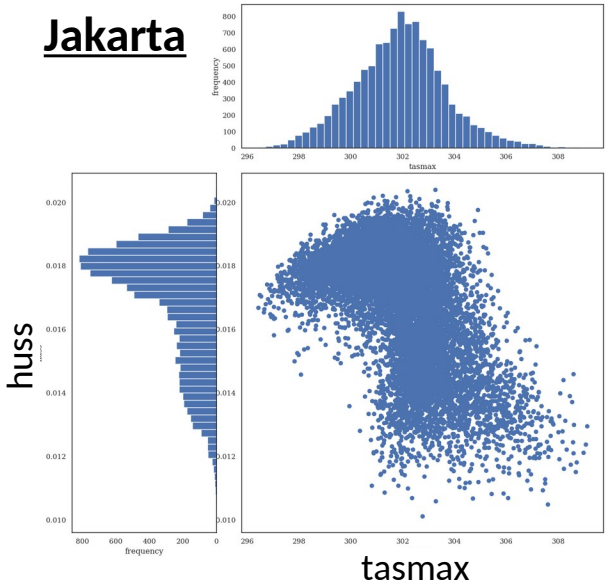
- Daily variables for period 2020-2050
  → 10 956 data points
- Scenario SSP 3.7-0

Tasmax and huss correlated?

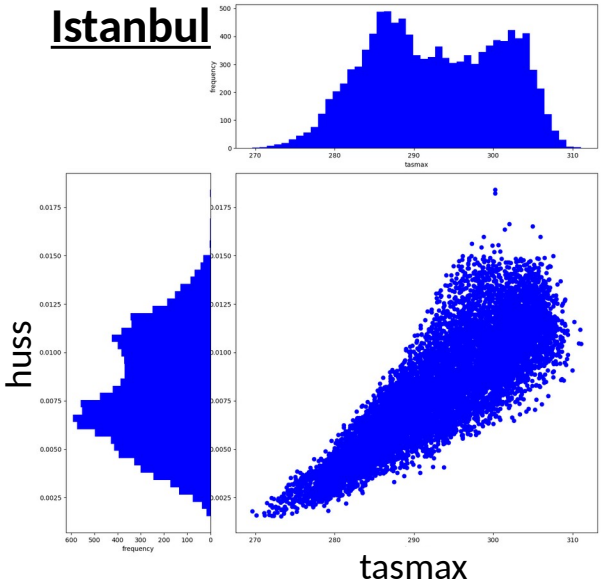
Tokyo



Jakarta

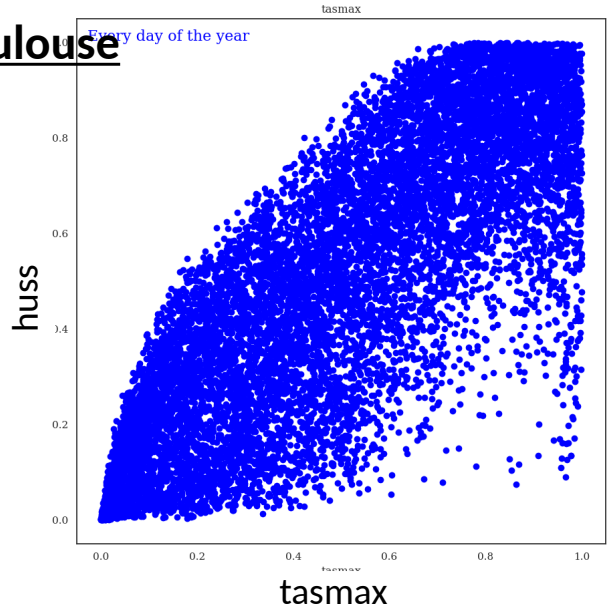


Istanbul

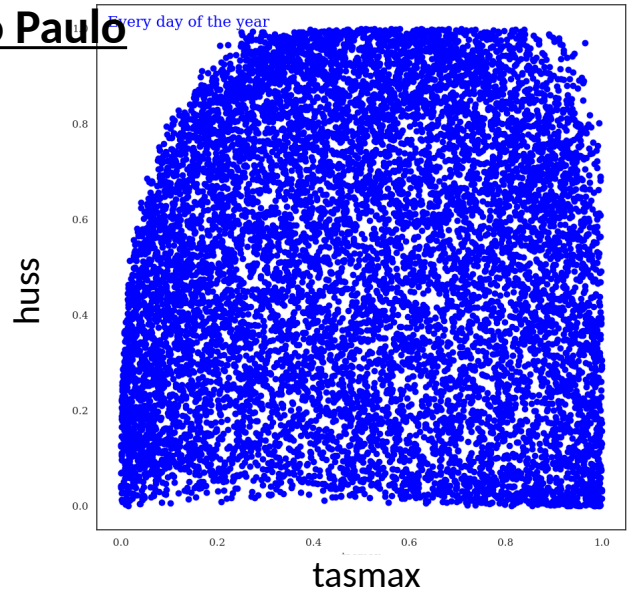


What the data looks like

Toulouse



Sao Paulo

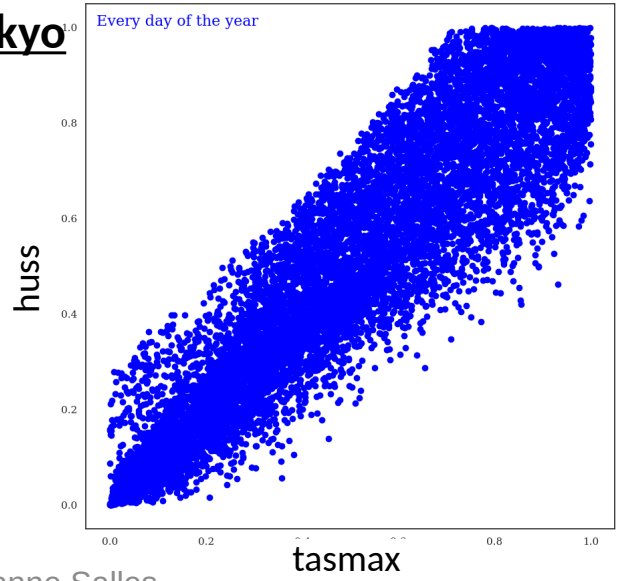


In the rank space

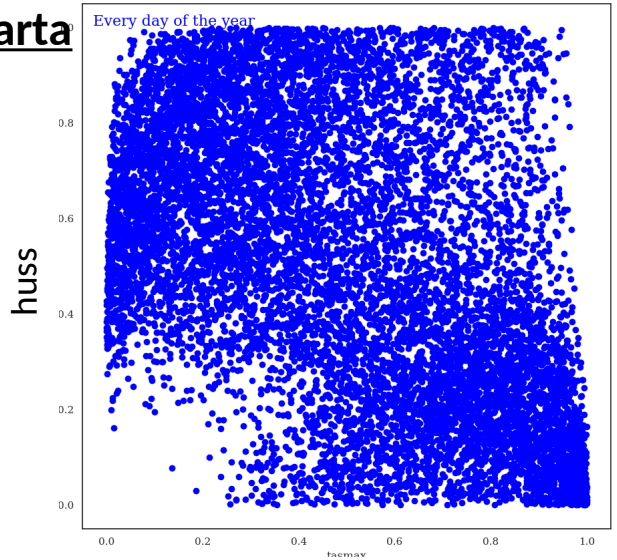
- Daily variables for period 2020-2050
  → 10 956 data points
- Scenario SSP 3.7-0

Tasmax and huss correlated?

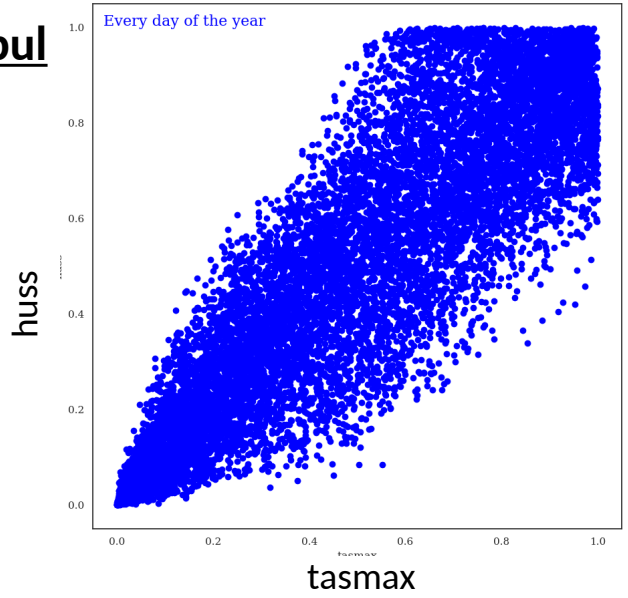
Tokyo



Jakarta



Istanbul



Focusing on extreme values

1. Summer
2. Quantiles
3. Critical threshold

Focusing on extreme values

1. **Summer**
2. Quantiles
3. Critical threshold

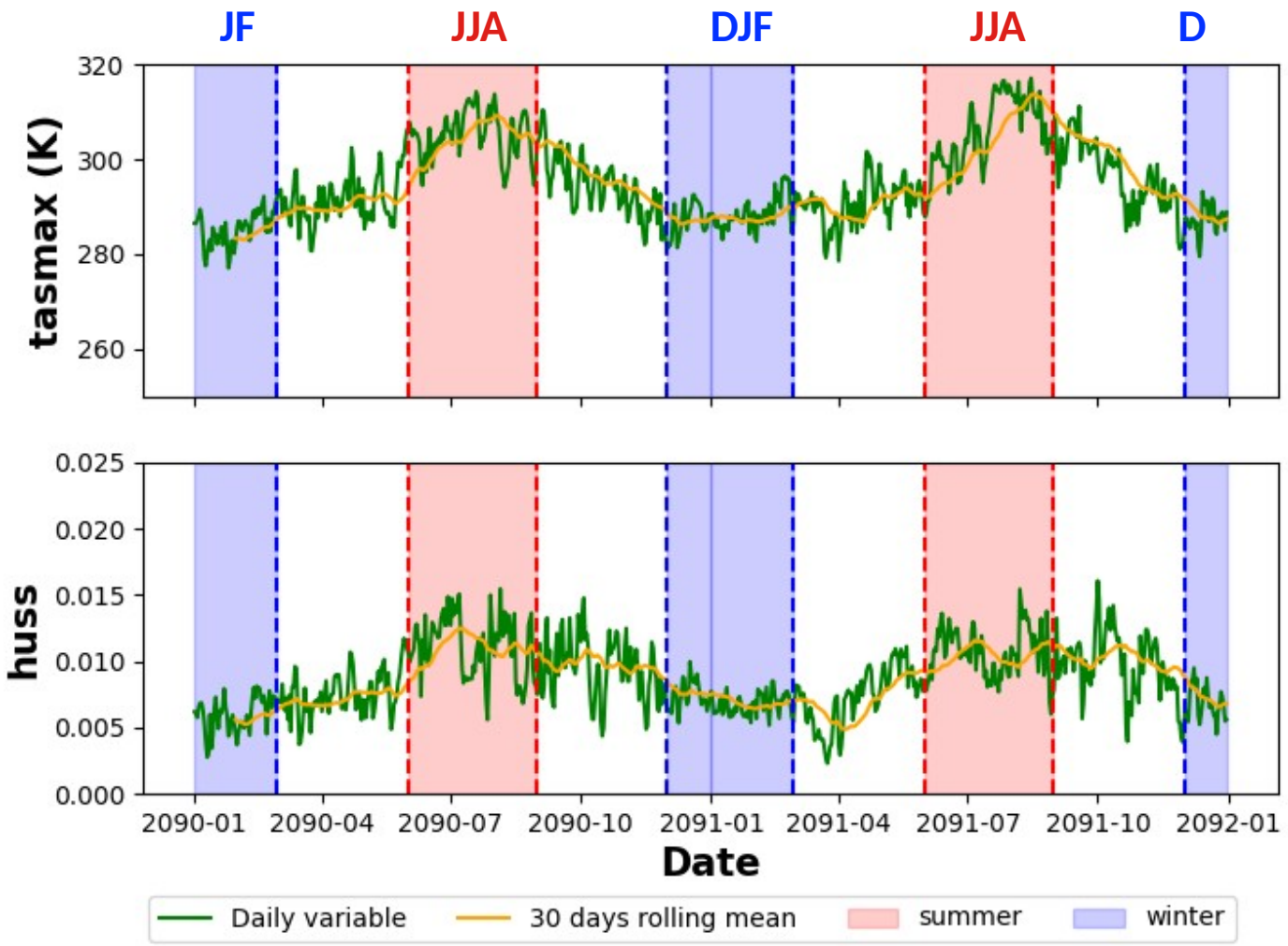
3-month summer restriction

Strict summer definition

North hemisphere:
June, July, August
South hemisphere:
December, January, February

- Data fluctuates a lot
- Summer season seems to be when the variables are the highest

Toulouse **Plot of daily data for 2 years**

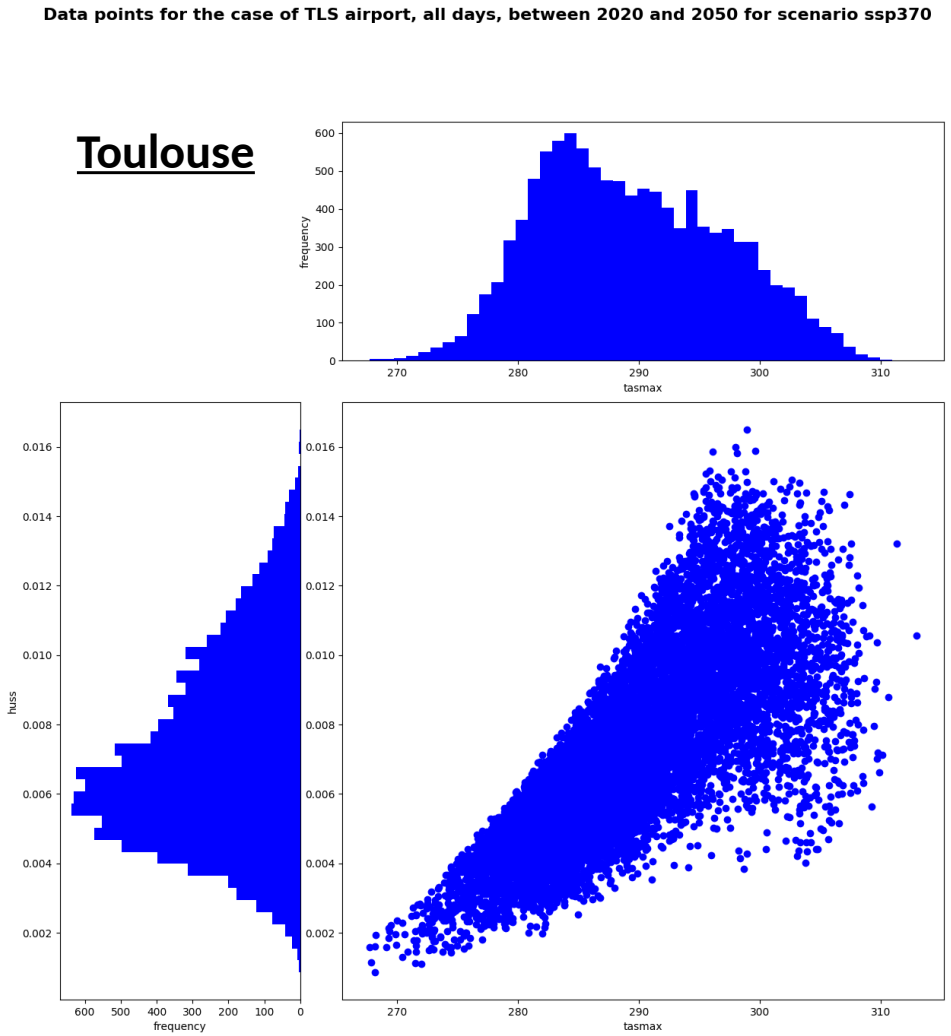


3-month summer restriction

Strict summer definition

North hemisphere:
June, July, August
South hemisphere:
December, January, February

Every day of the year:
10 956 points



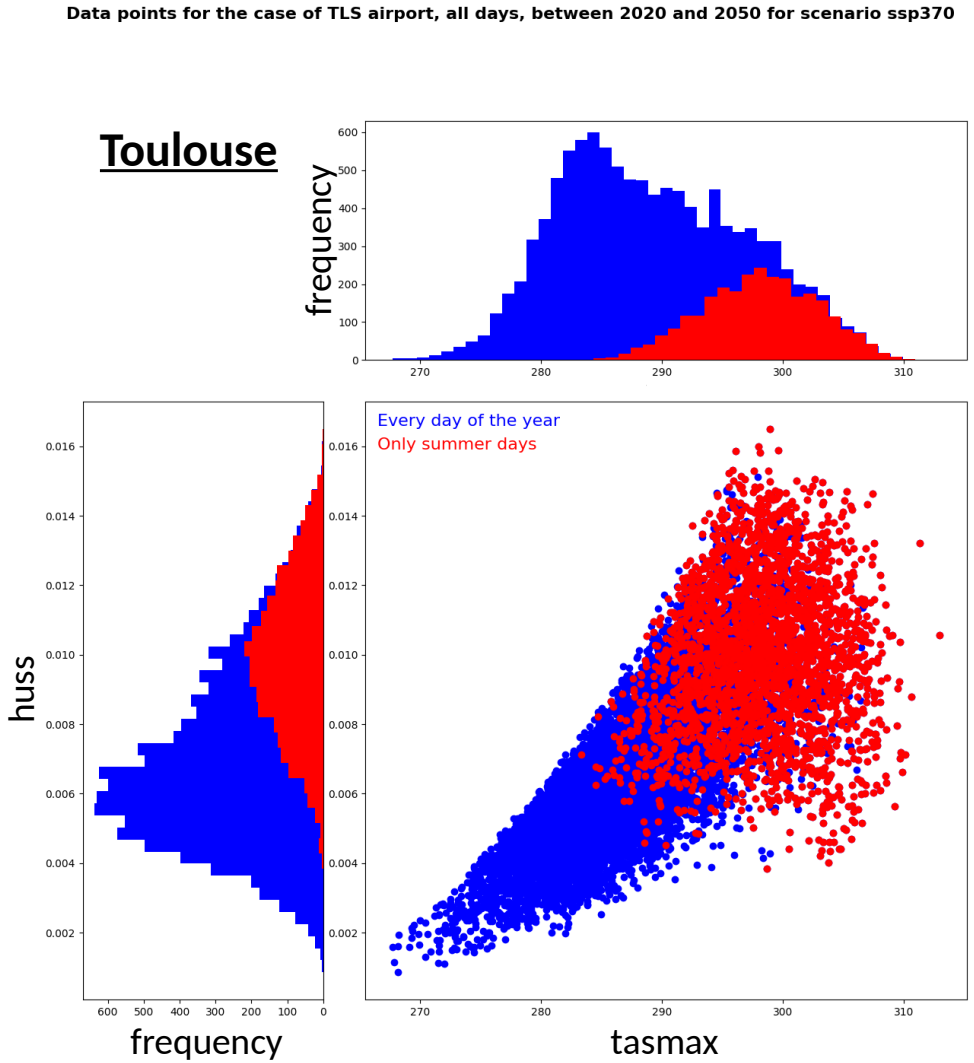
Correlation coefficients :
Pearson : 0.77
Spearman : 0.81

3-month summer restriction

Strict summer definition

North hemisphere:
June, July, August
South hemisphere:
December, January, February

Every day of the year:
10 956 points
Only summer days:
2 700 points



Correlation coefficients :
Pearson : 0.77
Spearman : 0.81
Pearson : 0.10
Spearman : 0.089

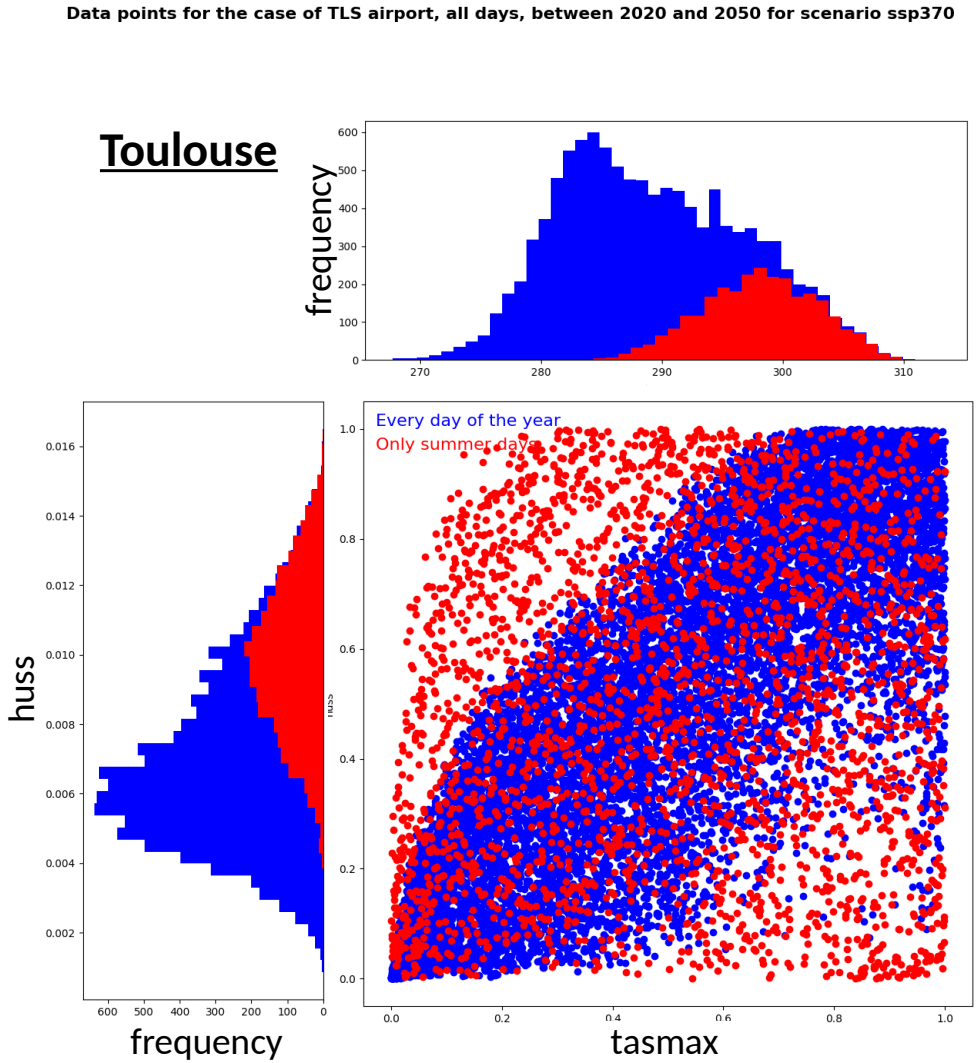
Pros: fixed window of 90 days per year for any case
Cons: doesn't necessarily apply to tropical climate

3-month summer restriction

Strict summer definition

North hemisphere:
June, July, August
South hemisphere:
December, January, February

Every day of the year:
10 956 points
Only summer days:
2 700 points



Correlation coefficients :
Pearson : 0.77
Spearman : 0.81
Pearson : 0.10
Spearman : 0.089

In the rank space

Pros: fixed window of 90 days per year for any case
Cons: doesn't necessarily apply to tropical climate

Other distributions for other airports

Strict summer definition

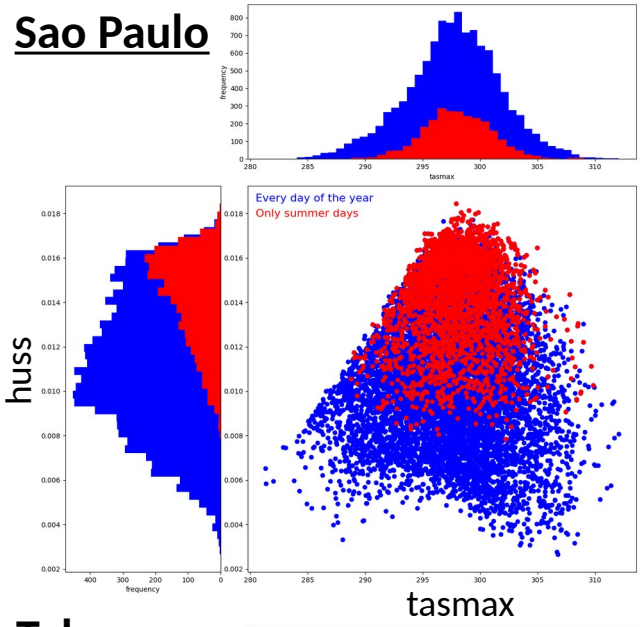
North hemisphere:
June, July, August

South hemisphere:
December, January, February

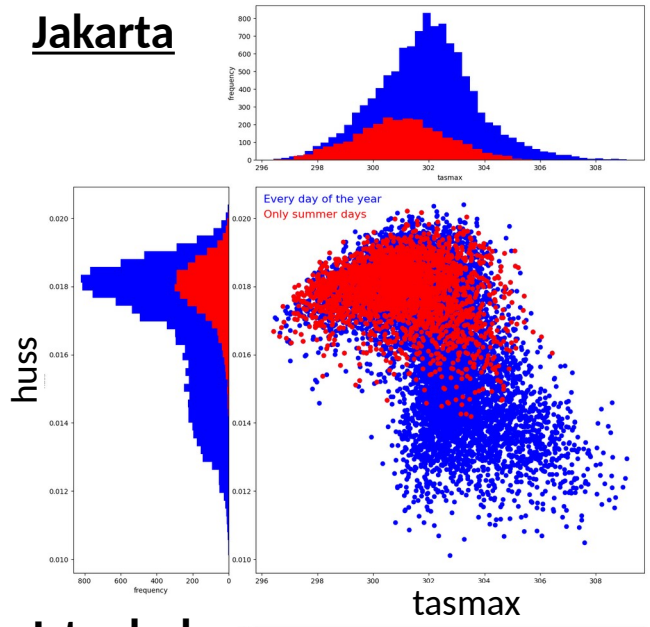
Every day of the year:
10 956 points

Only summer days:
2 700 points

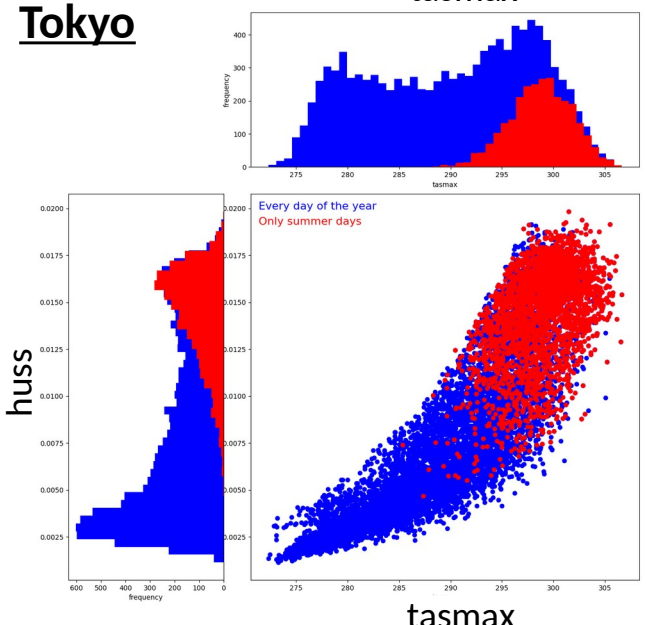
Sao Paulo



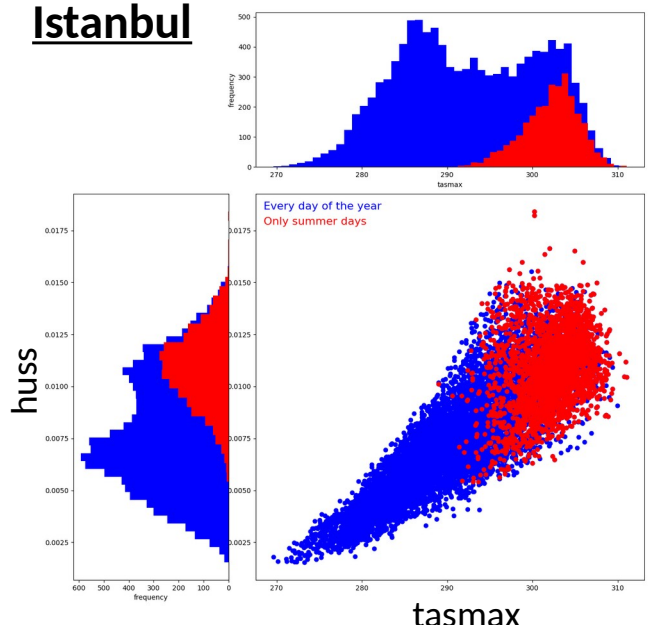
Jakarta



Tokyo



Istanbul



Other distributions for other airports

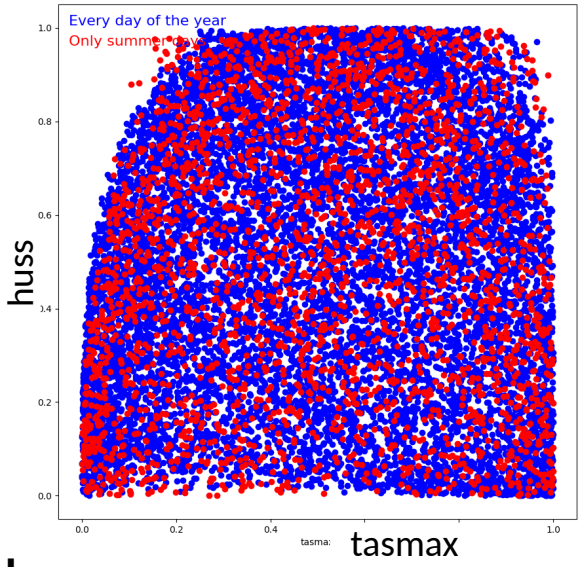
Strict summer definition

North hemisphere:
June, July, August
South hemisphere:
December, January, February

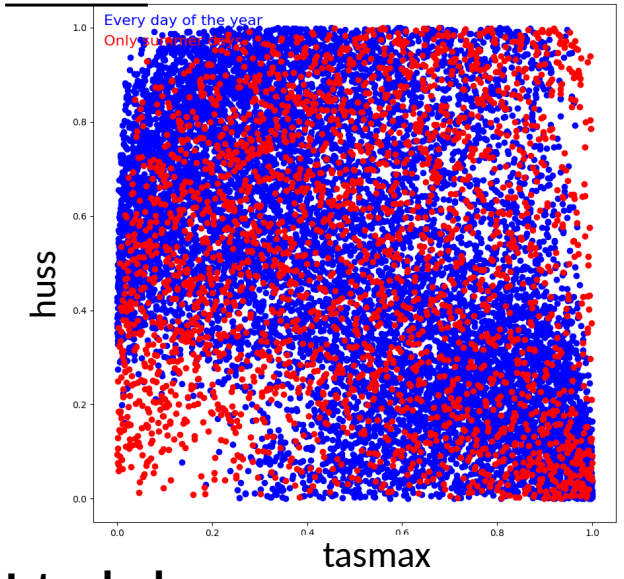
Every day of the year:
10 956 points
Only summer days:
2 700 points

In the rank space

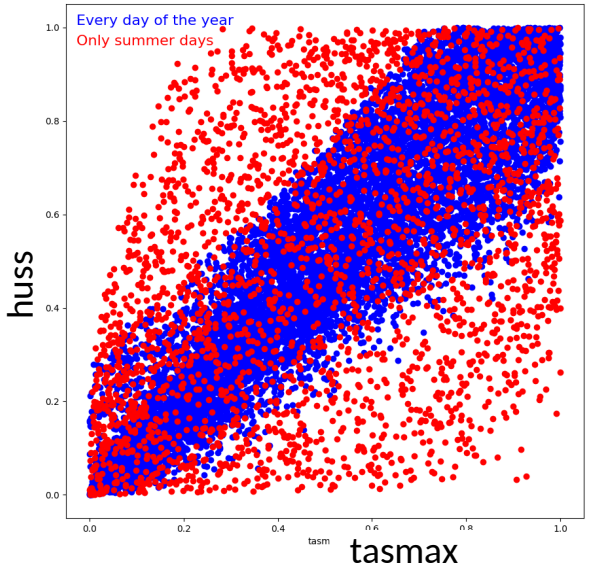
Sao Paulo



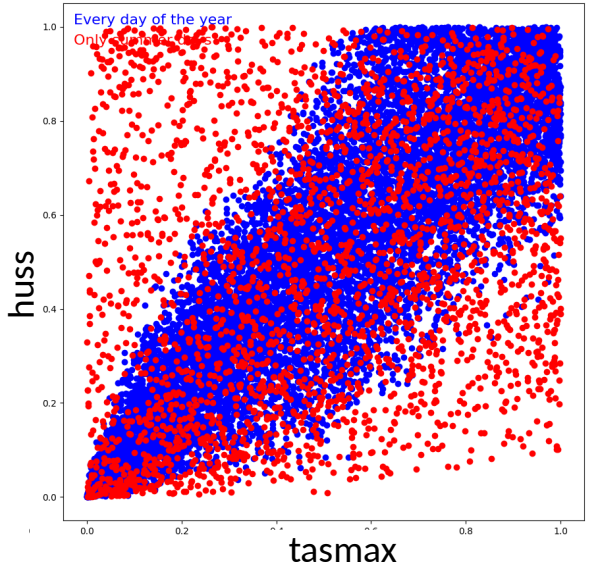
Jakarta



Tokyo



Istanbul



Focusing on extreme values

1. Summer
2. **Extreme quantiles**
3. Critical threshold

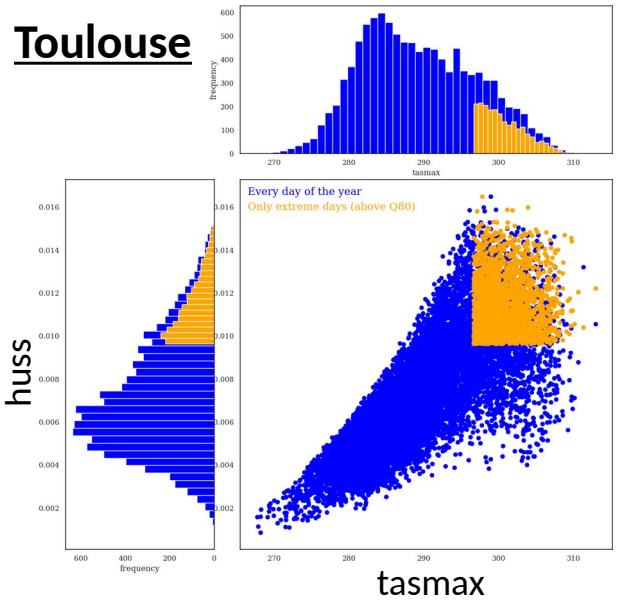
Extreme quantiles

Extreme values

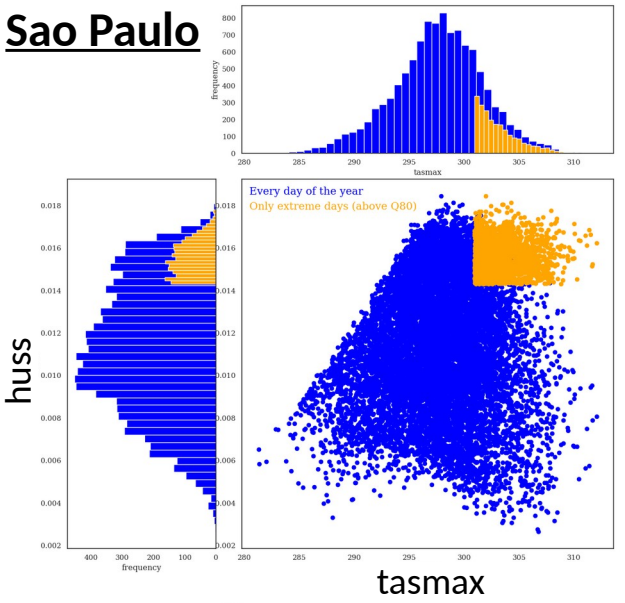
Defines as all values above the 80th percentile

Every day of the year:
10 956 points
Only extreme Q80 values:
2 192 points

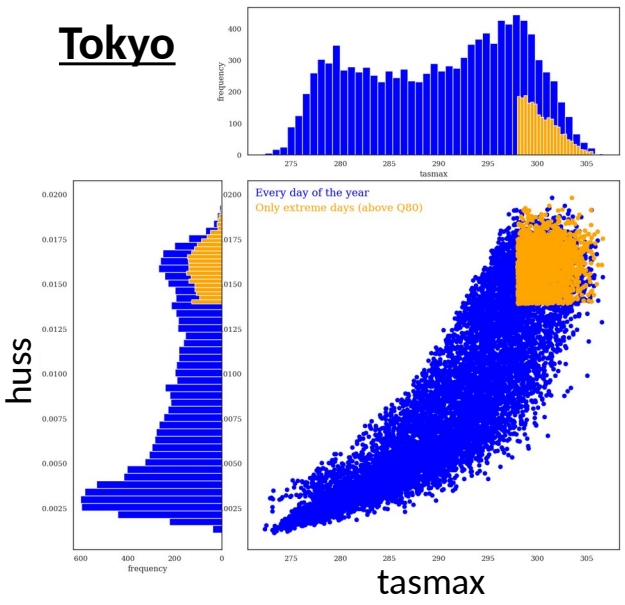
Toulouse



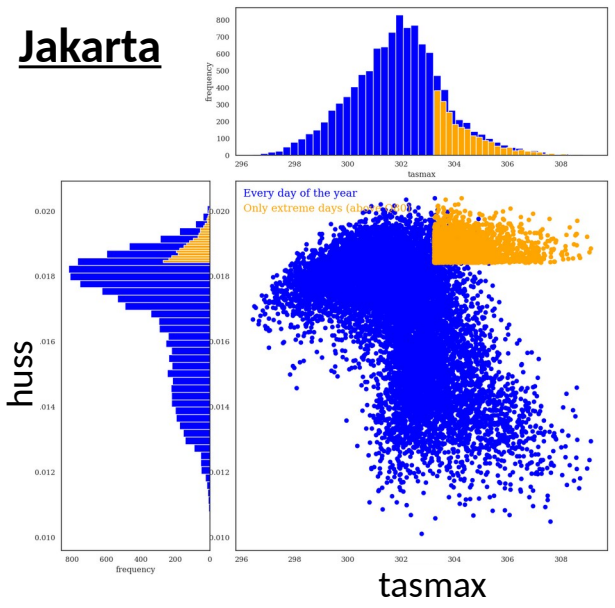
Sao Paulo



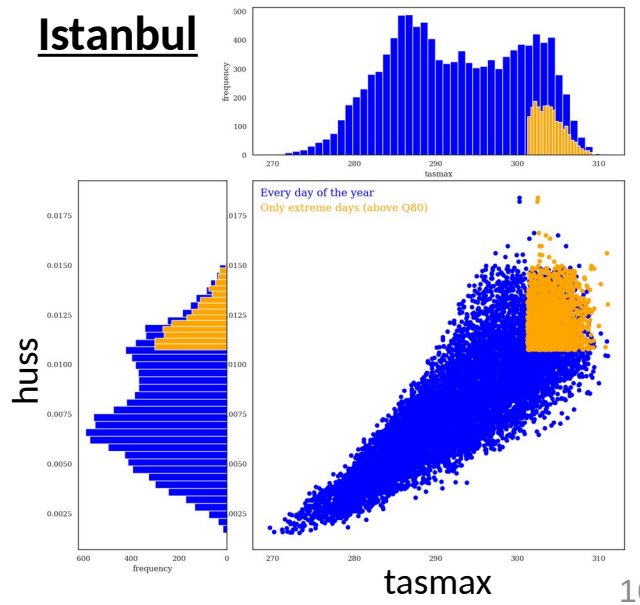
Tokyo



Jakarta



Istanbul



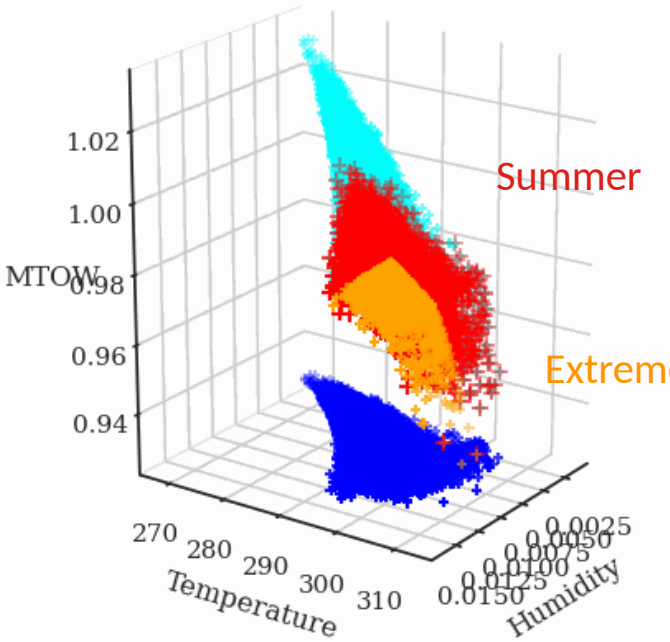
Propagation of extreme values

Output
MTOW

Aircraft model

Input data
tasmax
huss

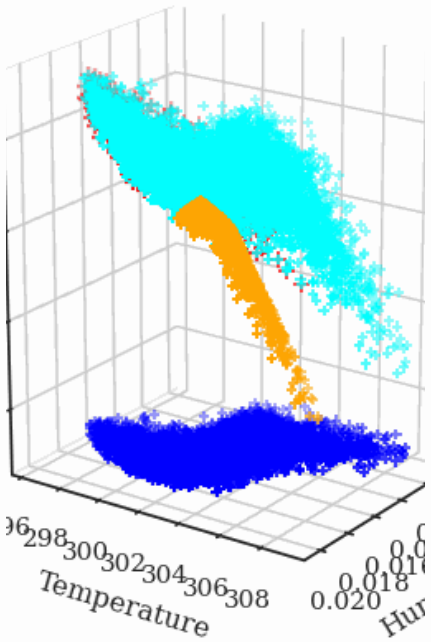
Toulouse



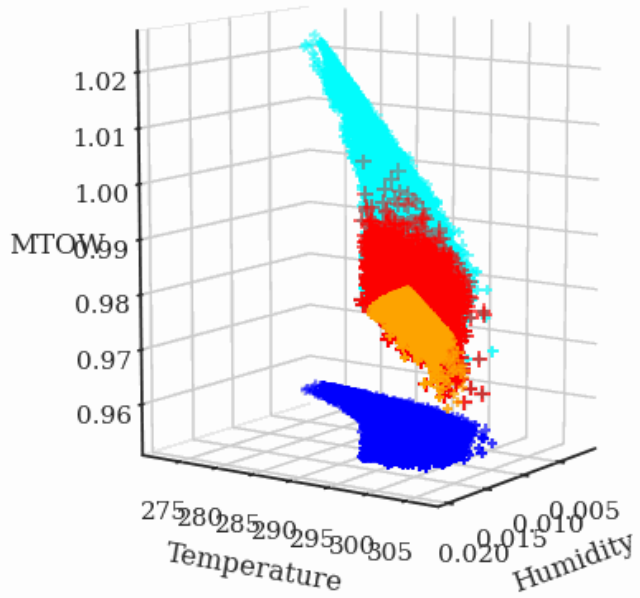
Summer

Extreme Q80

Jakarta



Tokyo



Max Take-Off Weight

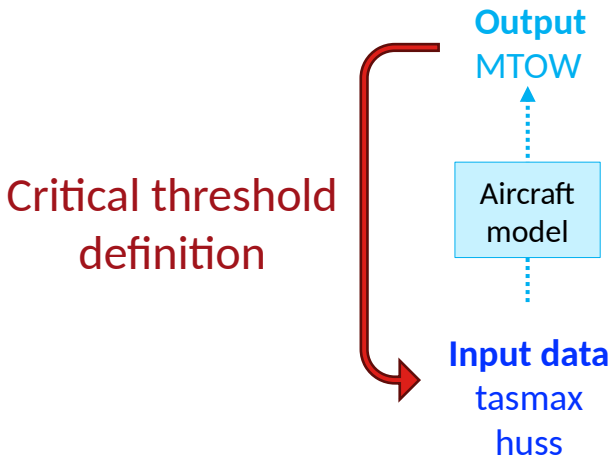
Focusing on extreme values

1. Summer
2. Extreme quantiles
3. **Critical threshold**

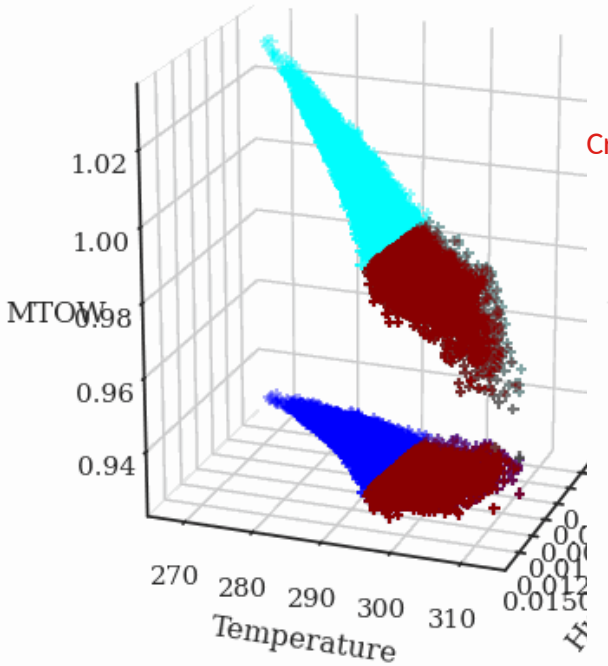
Critical MTOW threshold

MTOW threshold

Critical domain defined for

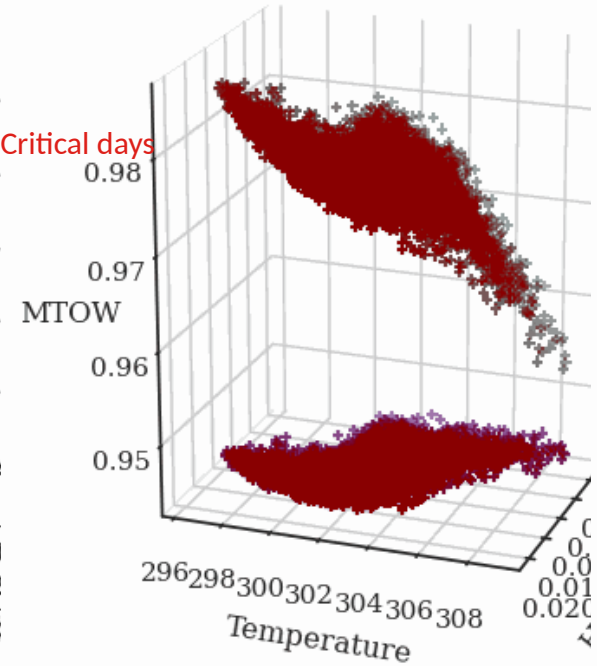


Toulouse



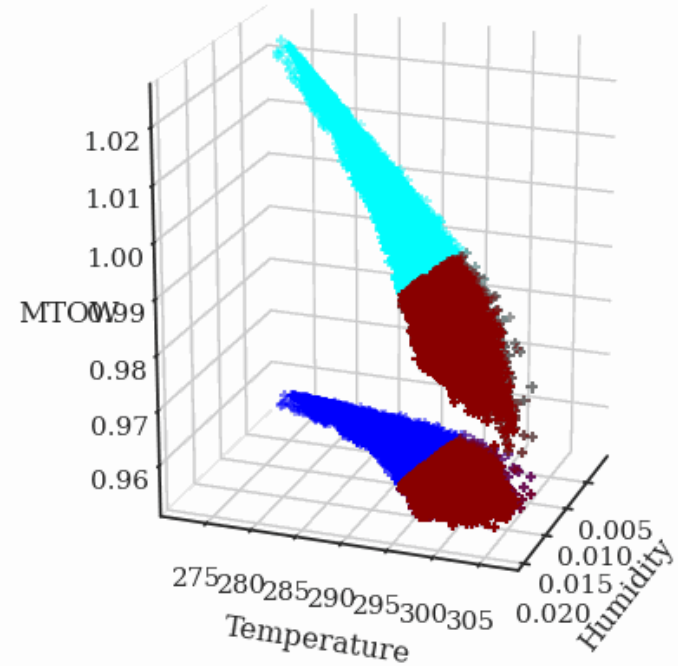
3 240 critical days
(29.6 % of days)

Jakarta



10 958 critical days
(100% of days)

Tokyo



4 400 critical days
(40.2% of days)

→ Focuses on all input variables that give performance defined as critical

Con: Variable number of critical data

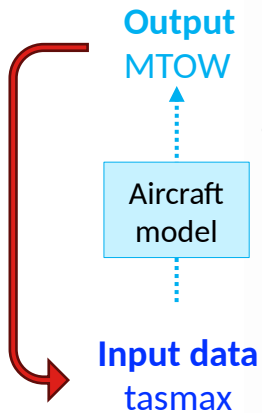
Max Take-Off Weight

Critical MTOW threshold

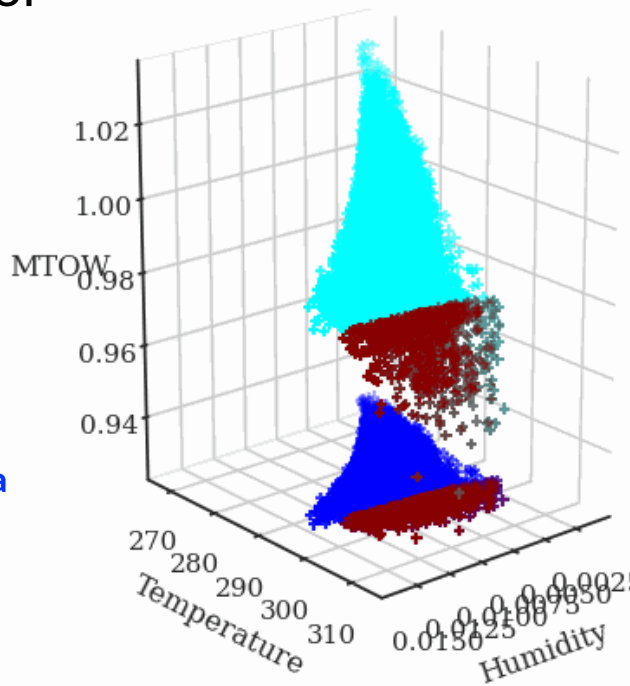
MTOW threshold

Critical domain defined for

Critical threshold definition

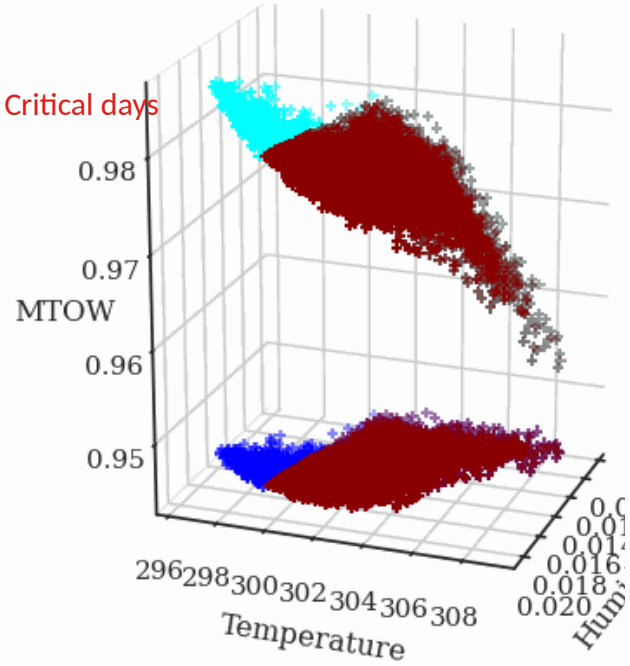


Toulouse



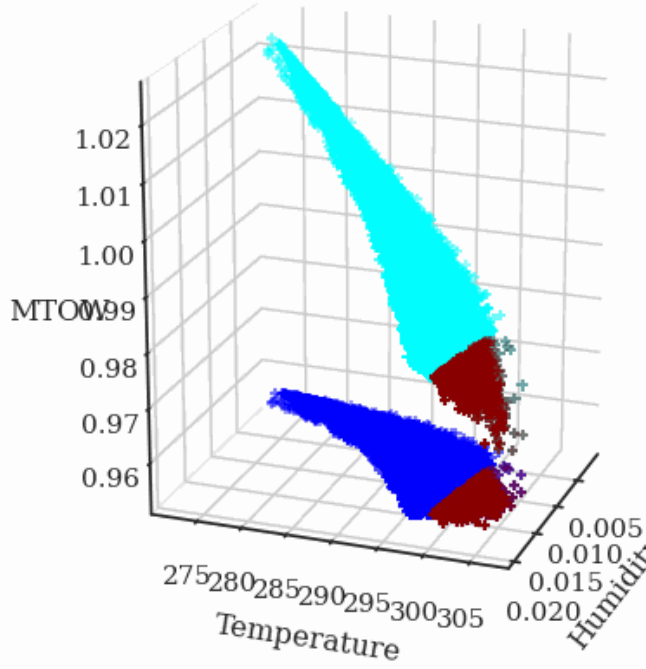
3 240 critical days
(7.7 % of days)

Jakarta



9 669 critical days
(88.2% of days)

Tokyo



993 critical days
(9.0% of days)

→ Focuses on all input variables that give performance defined as critical

Con: Variable number of critical data

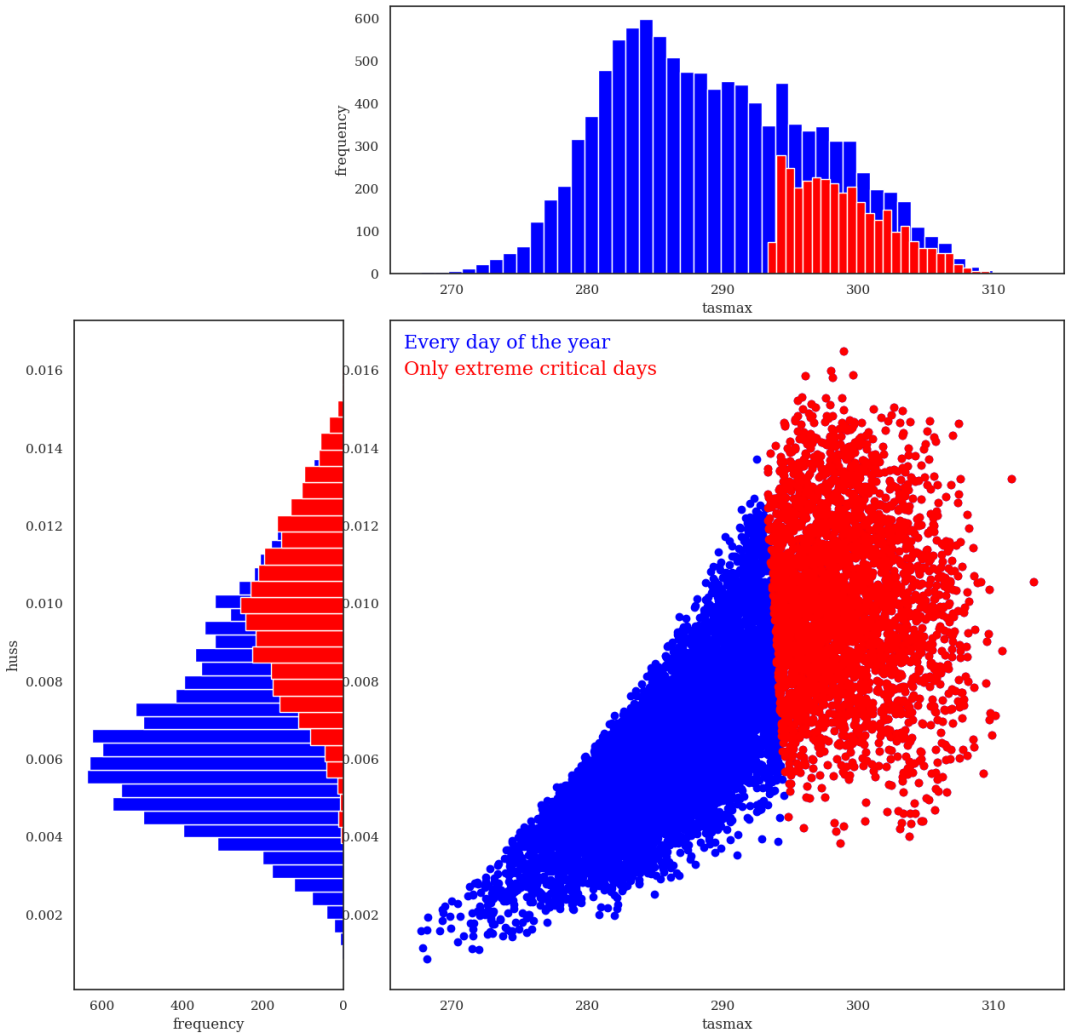
Max Take-Off Weight

Fitting input distribution and sensitivity analysis

For critical data

Input distribution

Toulouse Threshold =

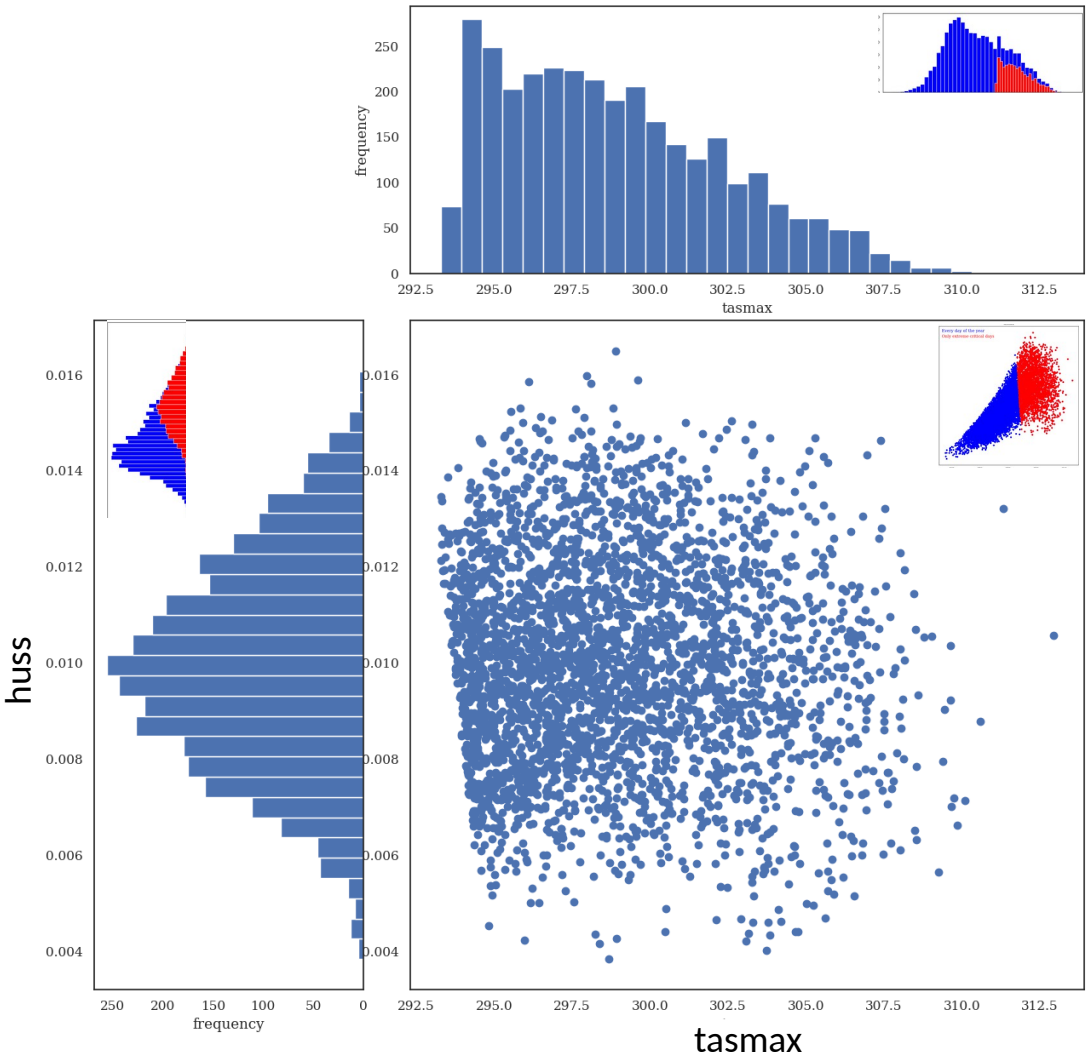


Every day of the year:
10 956 points
Only critical days:
3 240 points

Critical input distribution

Toulouse

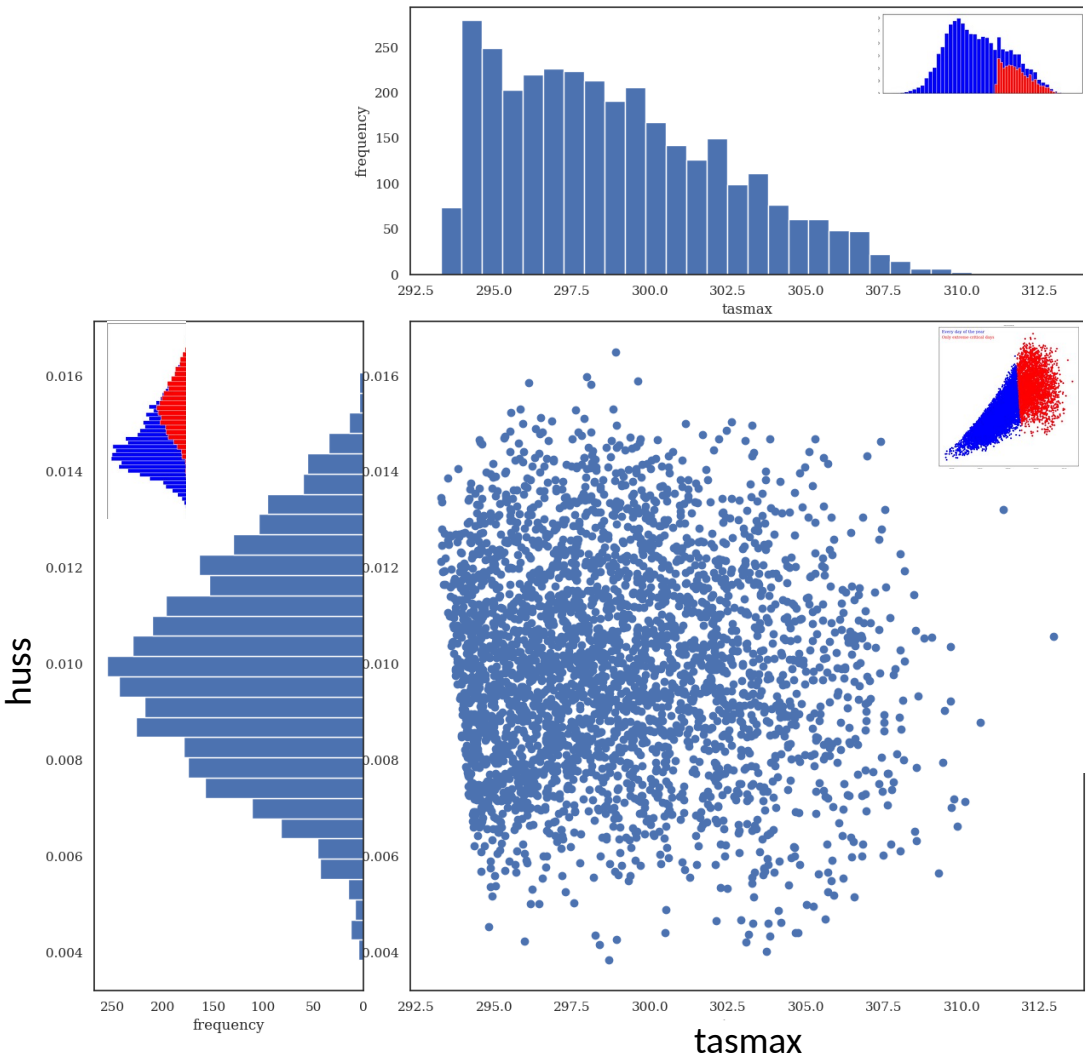
Threshold =



Dependency

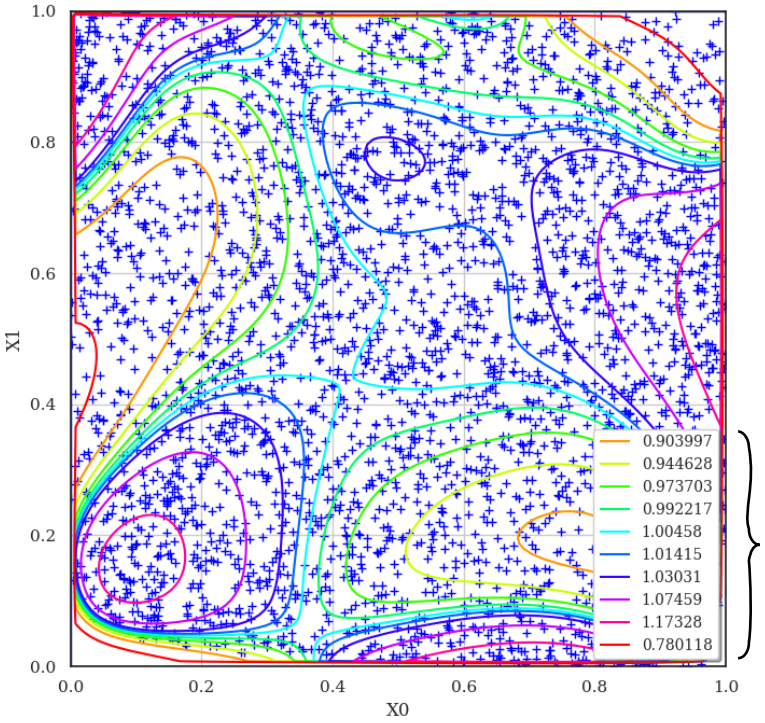
Toulouse

Threshold =



Fitting an Empirical Bernstein Copula

+ Sample in rank space

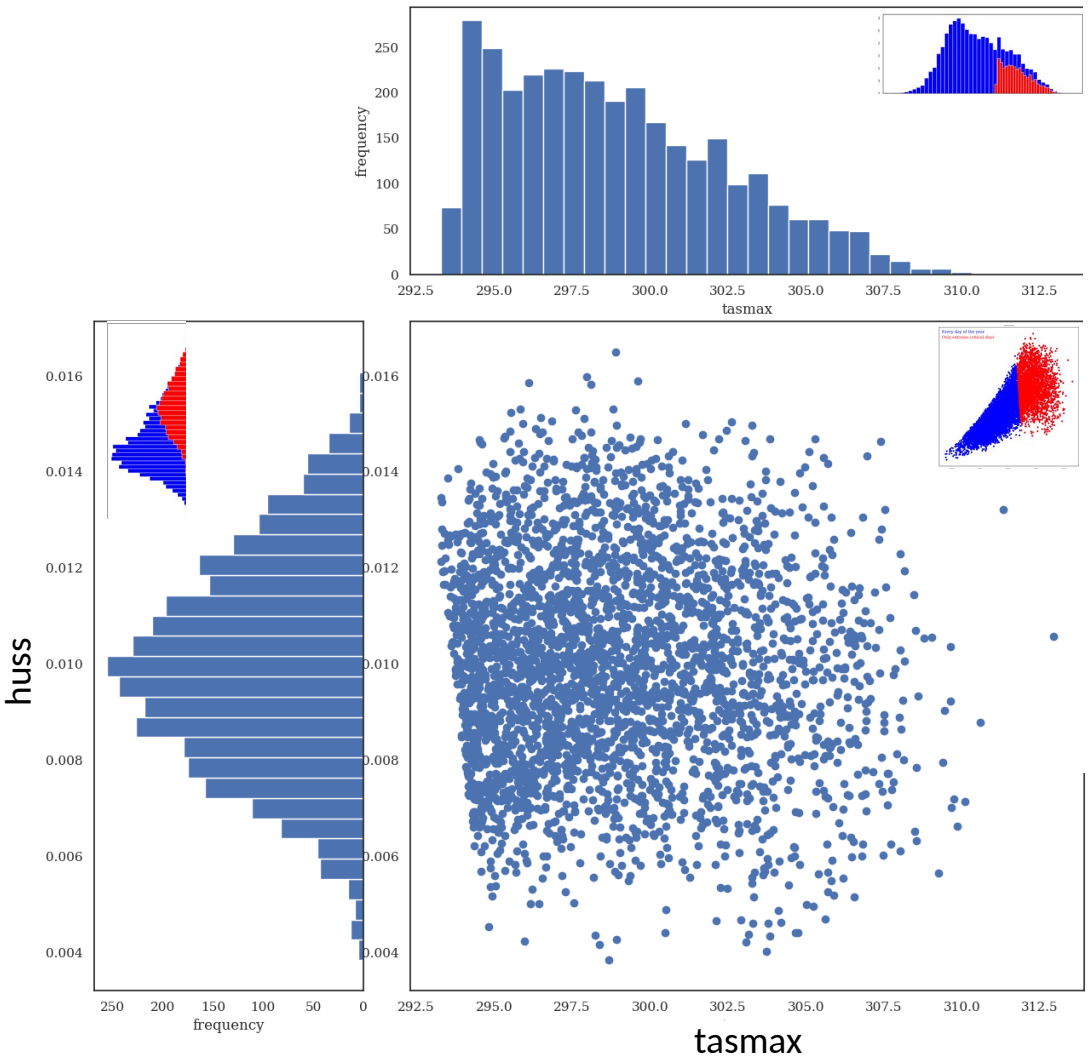


Copula PDF contours

Dependency

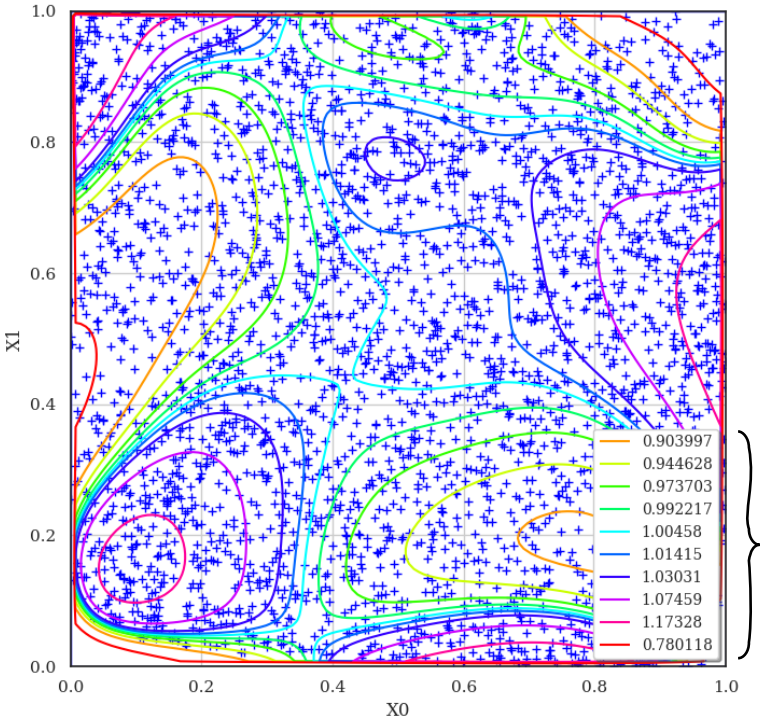
Toulouse

Threshold =



Fitting an Empirical Bernstein Copula

+ Sample in rank space



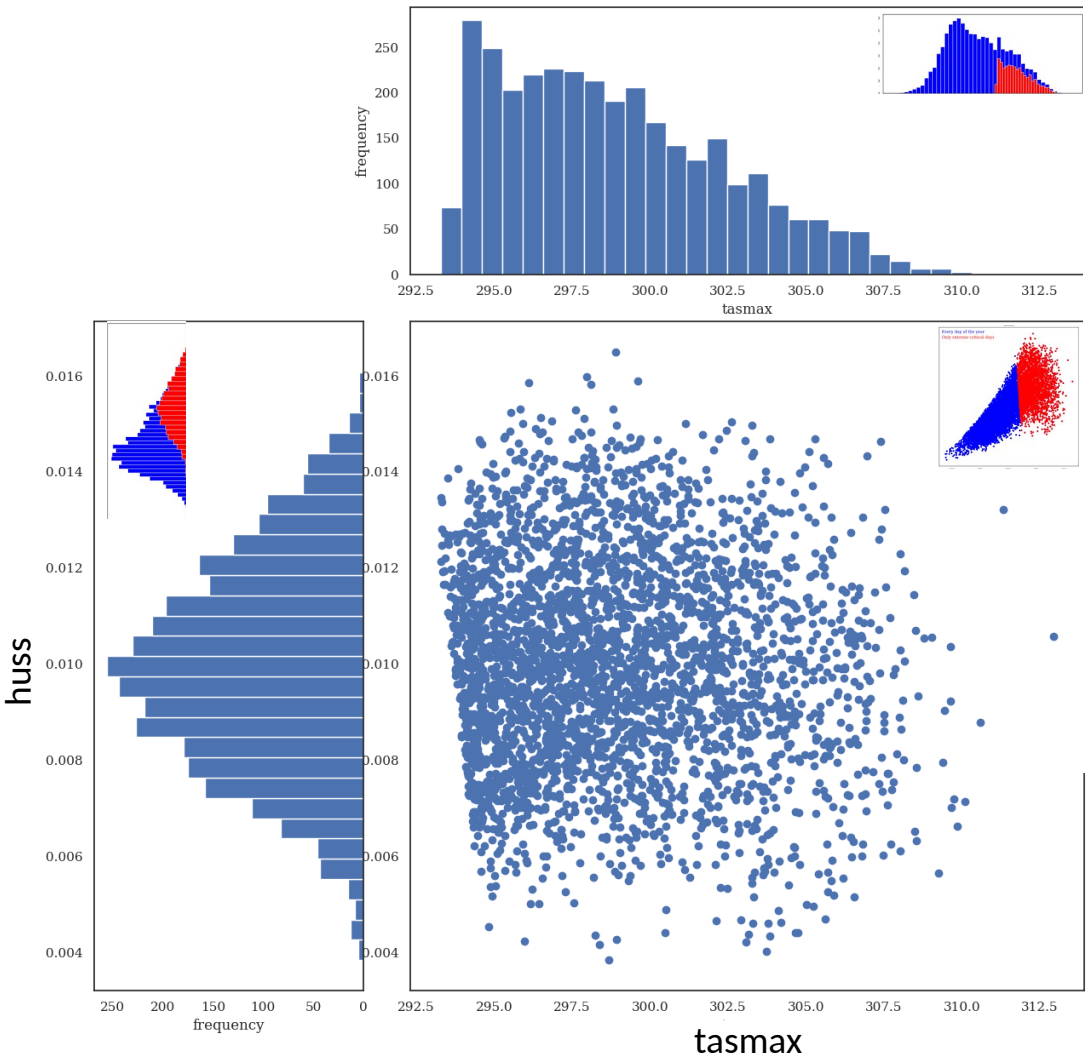
Copula PDF contours

Difference between lowest and highest density: 0.27

Correlation coefficients
Pearson: -0.048
Spearman: -0.018

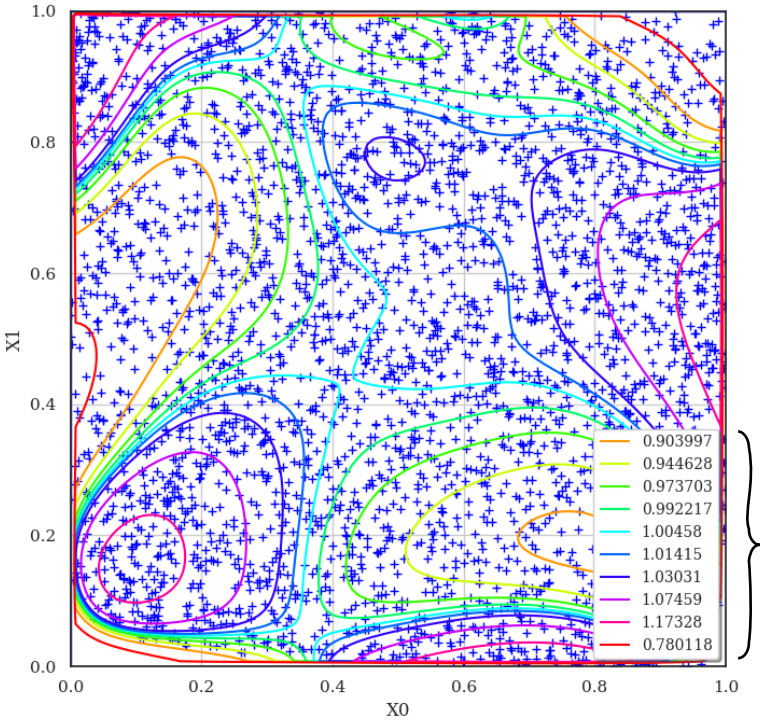
Dependency

Toulouse Threshold =



Fitting an Empirical Bernstein Copula

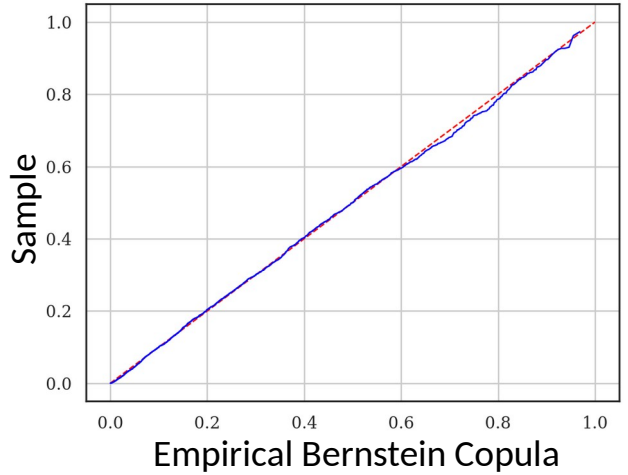
+ Sample in rank space



Copula PDF contours

Difference between lowest and highest density: 0.27

Kendall plot



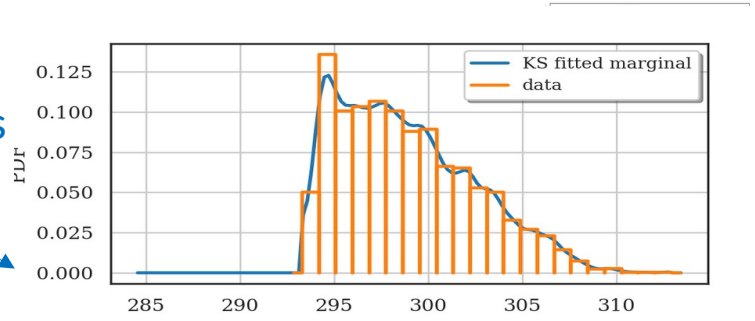
Correlation coefficients
Pearson: -0.048
Spearman: -0.018

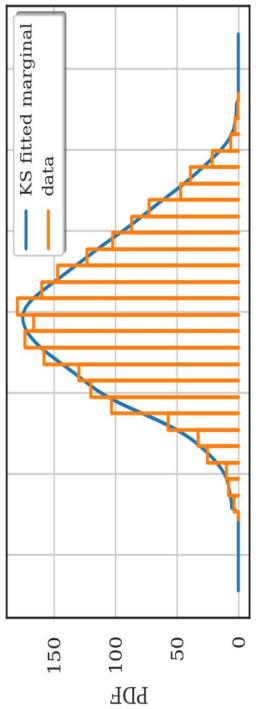
Joint composed distribution

Toulouse

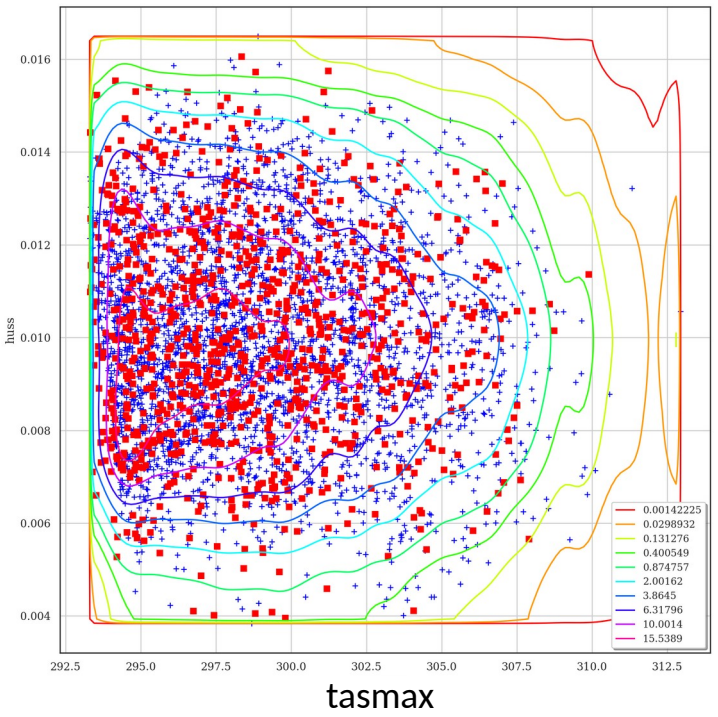
Threshold =

Fitted marginals with Kernel Smoothing





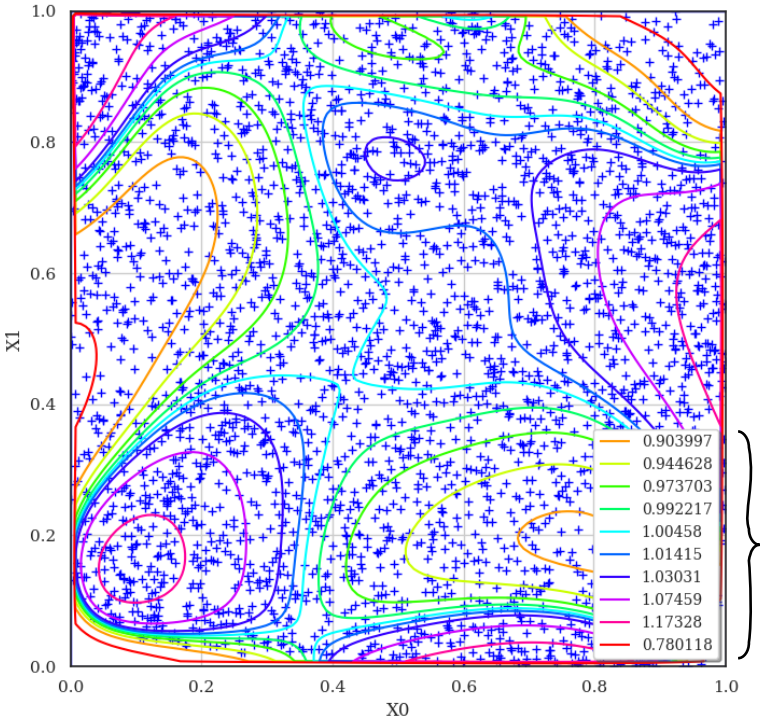
huss



tasmax

Fitting an Empirical Bernstein Copula

+ Sample in rank space



Copula PDF contours

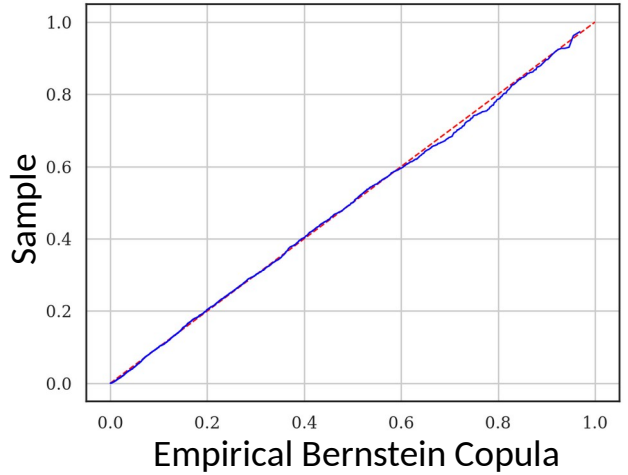
Difference between lowest and highest density: 0.27

Joint distribution contours

\+ Data sample

▪ Sample on fitted PDF

Kendall plot



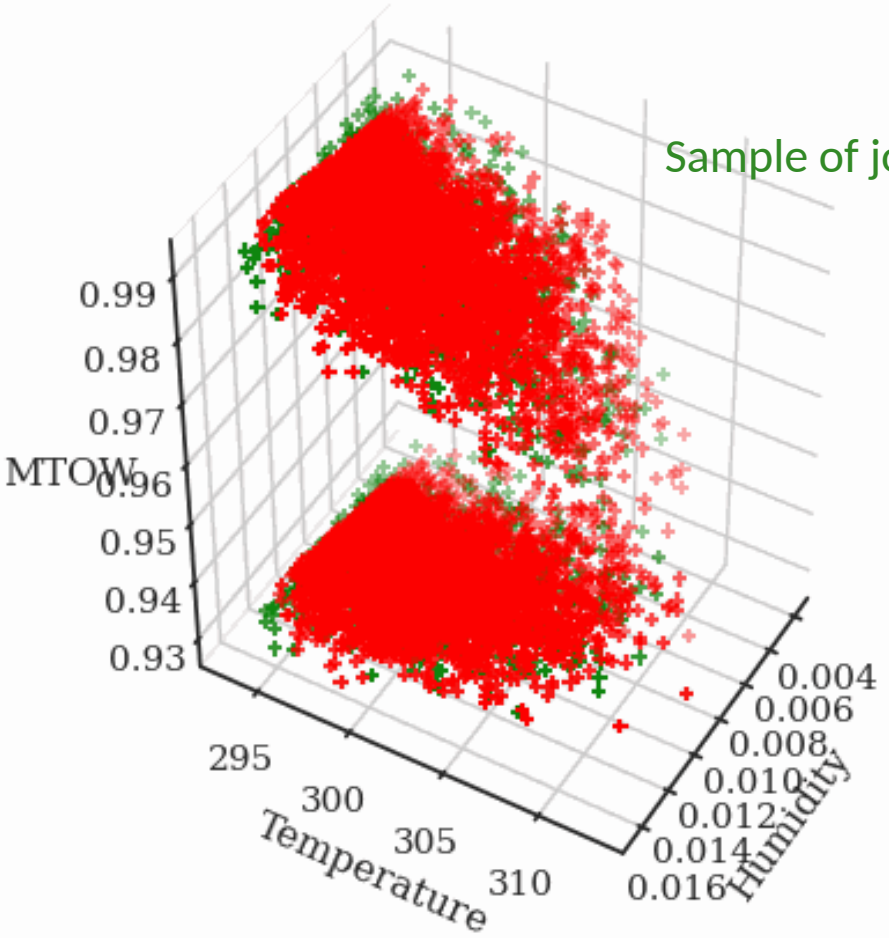
Correlation coefficients

Pearson: -0.048

Spearman: -0.018

Propagated results

Toulouse



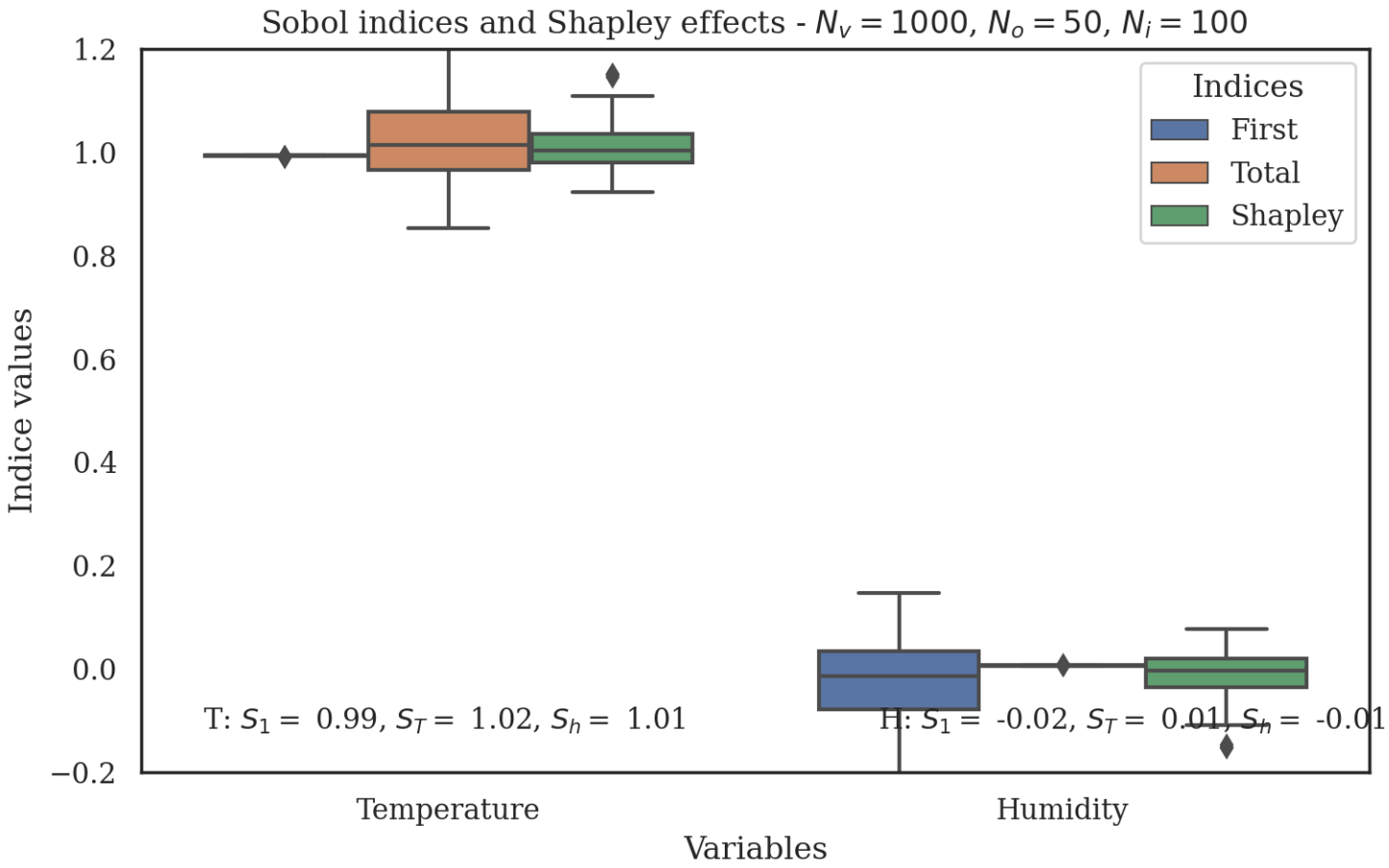
Sample of joint composed distribution

Critical propagated data

Max Take-Off Weight

Sensitivity Analysis

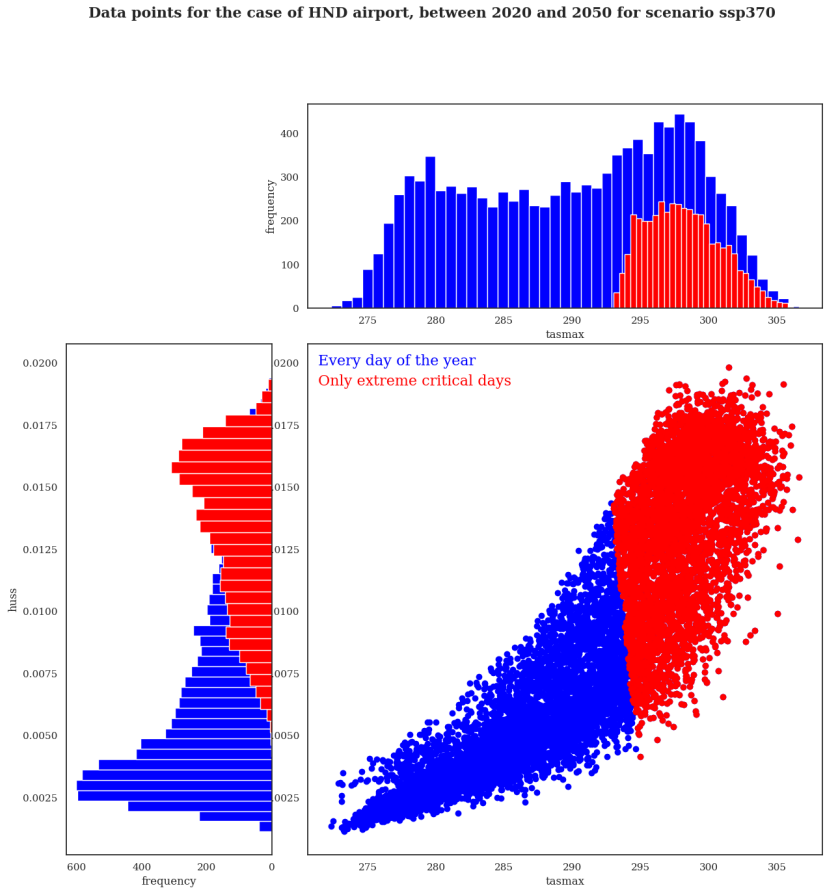
Toulouse



Critical input distribution

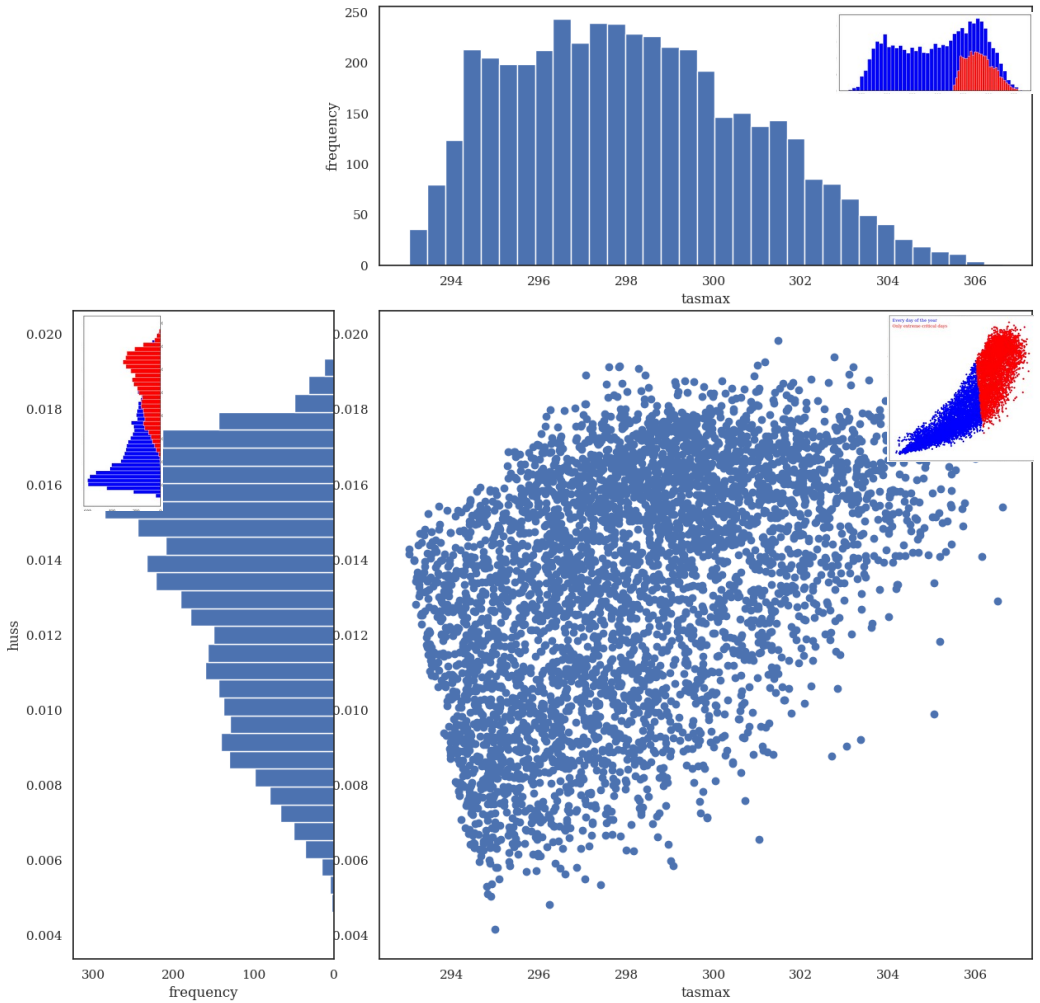
Tokyo

Threshold =



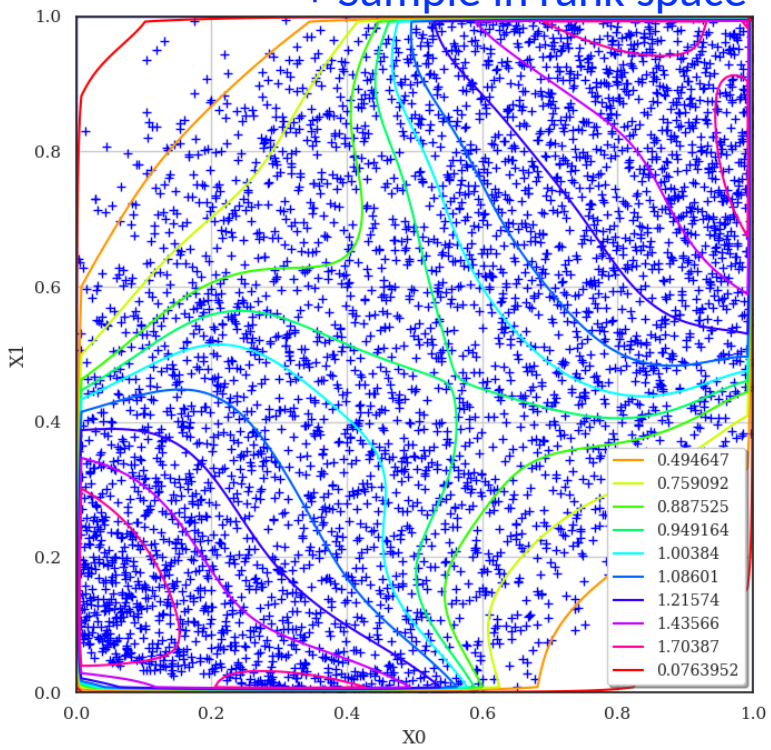
Dependency

Tokyo Threshold =



Fitting an Empirical Bernstein Copula

+ Sample in rank space



Copula PDF contours

Difference between lowest and highest density: 1.21

Correlation coefficients

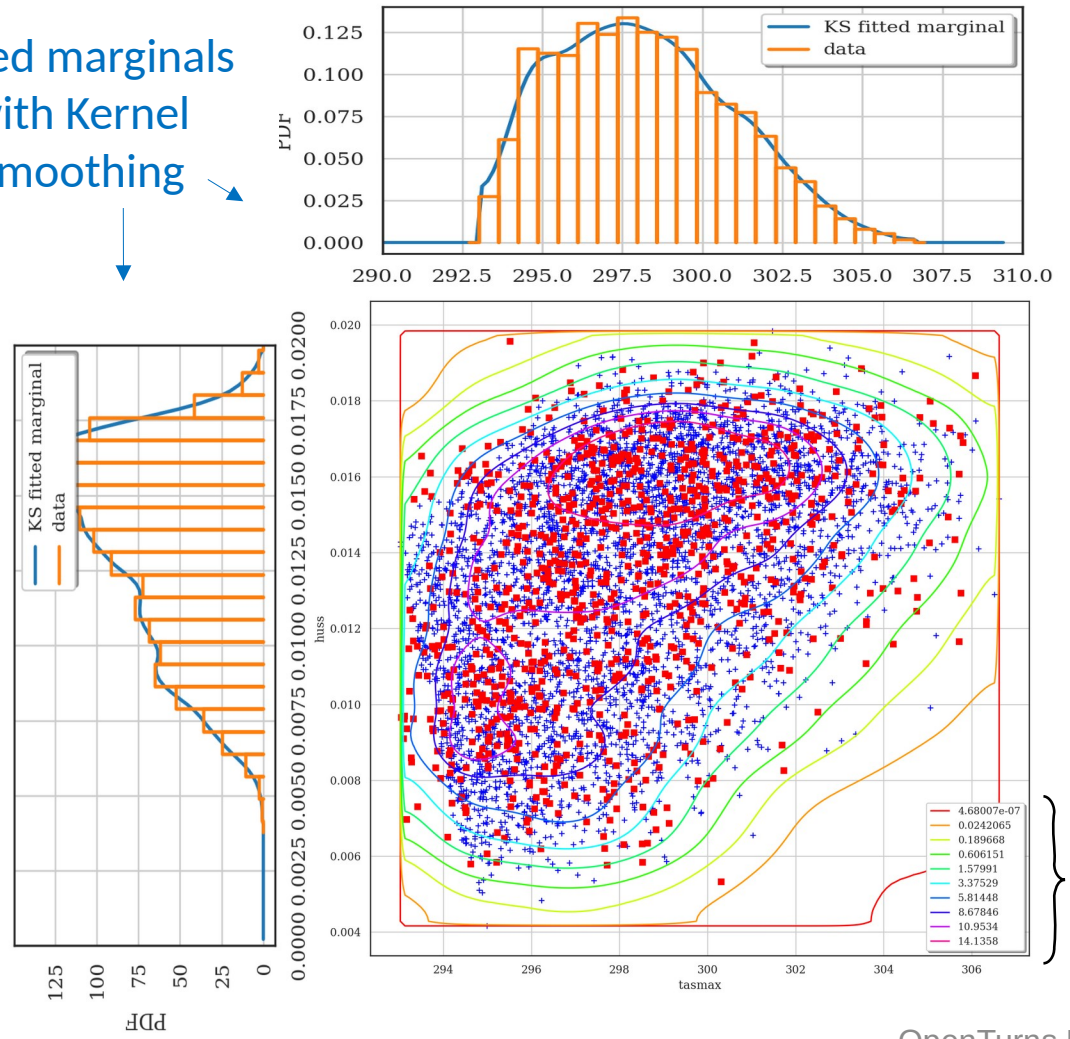
Pearson: 0.45

Spearman: 0.47

Joint composed distribution

Tokyo Threshold =

Fitted marginals with Kernel Smoothing



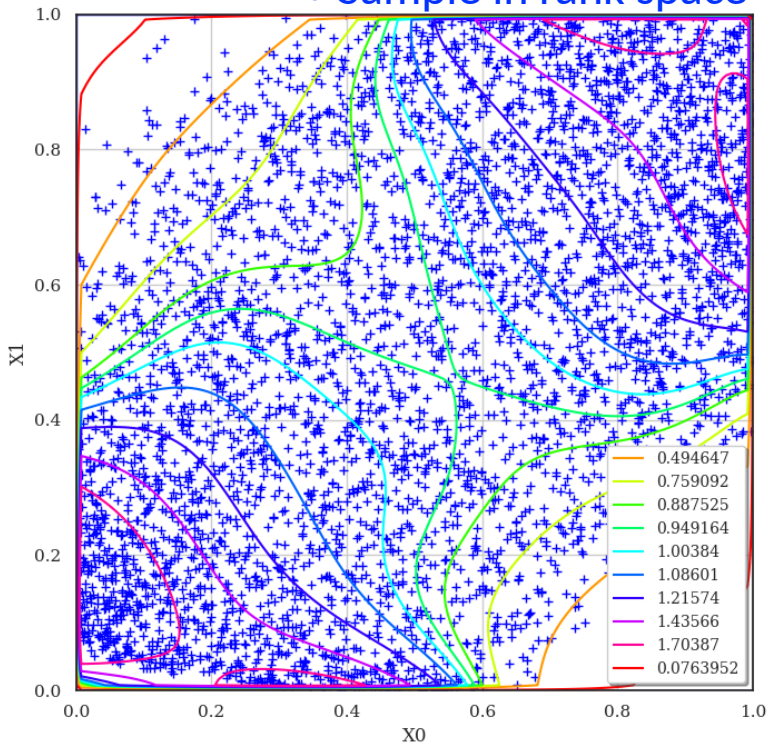
Joint distribution contours

\+ Data sample

▪ Sample on fitted PDF

Fitting an Empirical Bernstein Copula

\+ Sample in rank space



Copula PDF contours

Difference between lowest and highest density: 1.21

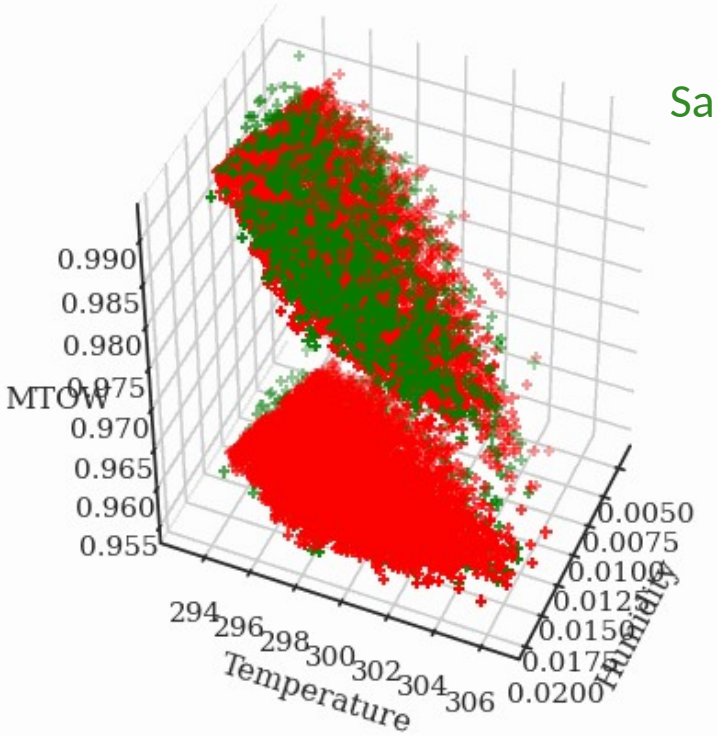
Correlation coefficients

Pearson: 0.45

Spearman: 0.47

Propagated result

Tokyo Threshold =



Sample of joint composed distribution

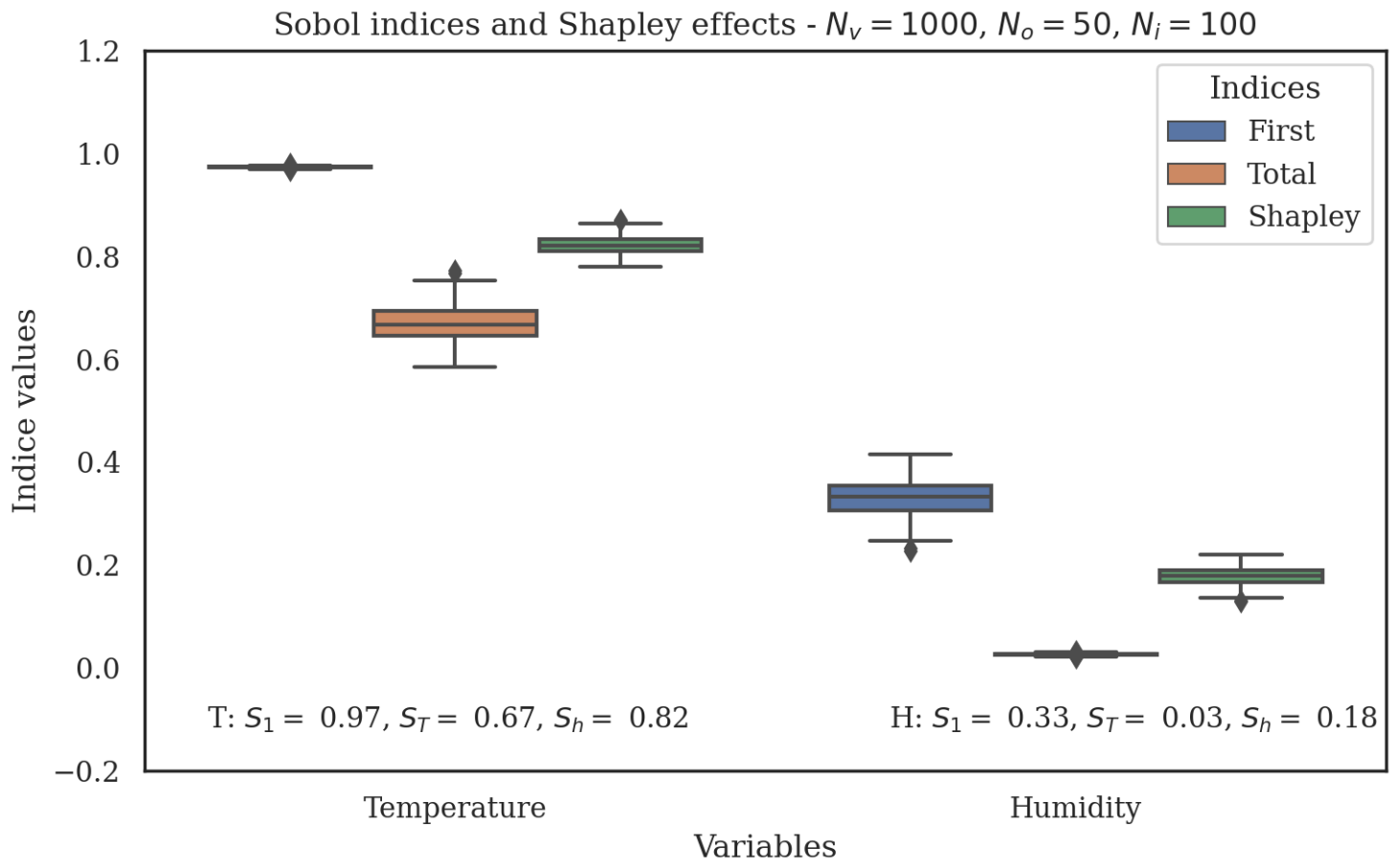
Critical propagated data

Max Take-Off Weight

Sensitivity Analysis

Tokyo

Threshold =

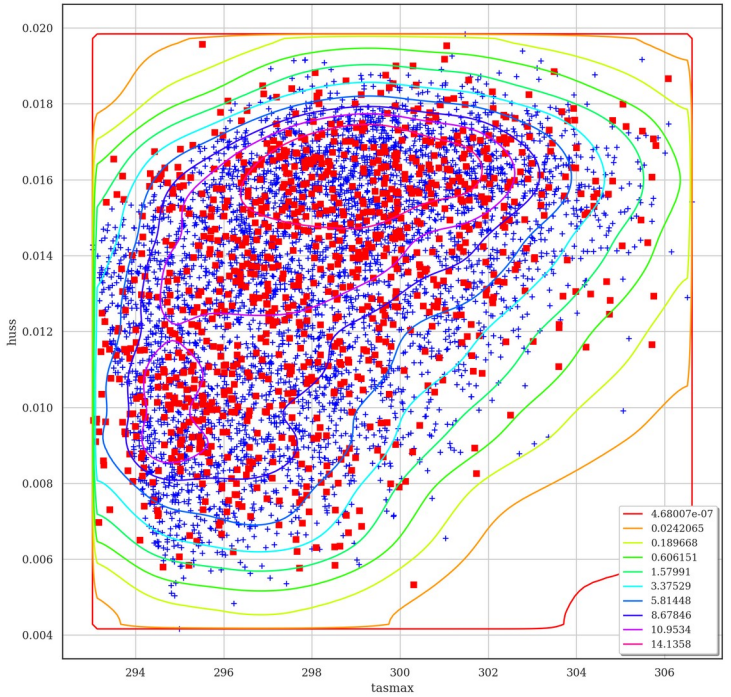


Importance of dependency

Tokyo

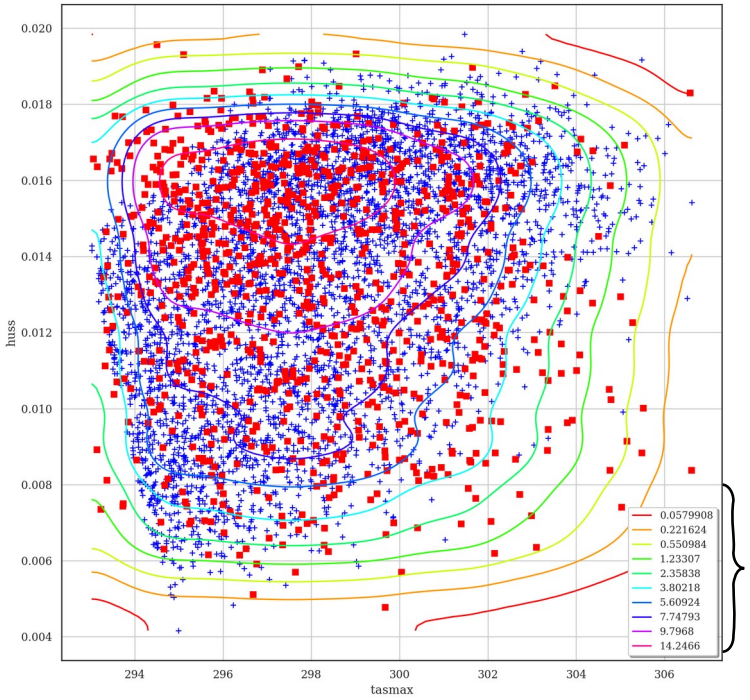
Threshold =

With Empirical Bernstein copula



Joint distribution contours

With independent copula



Joint distribution contours

\+ Data sample

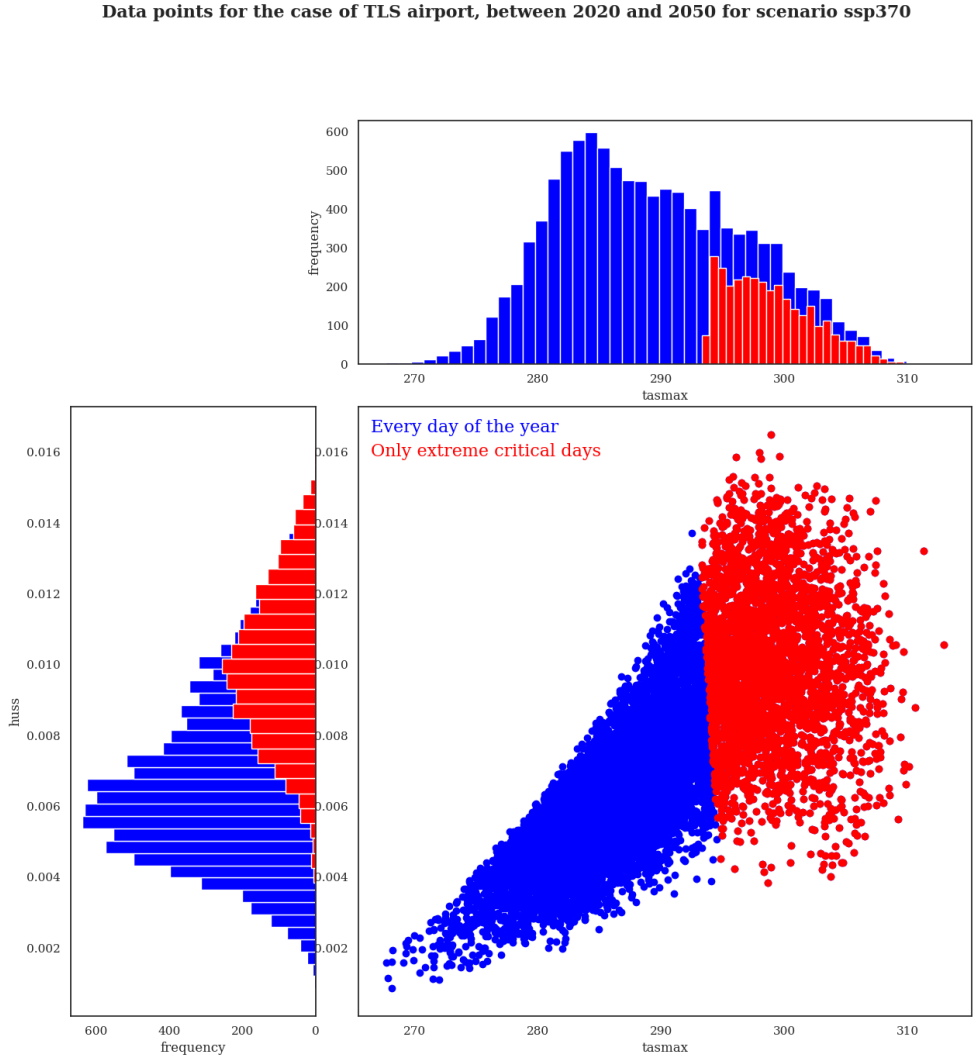
▪ Sample on fitted PDF

Shapley indices:

Temperature	S_h=0.82	S_h=0.94
Humidity	S_h=0.18	S_h=0.06

Why focus on extreme values?

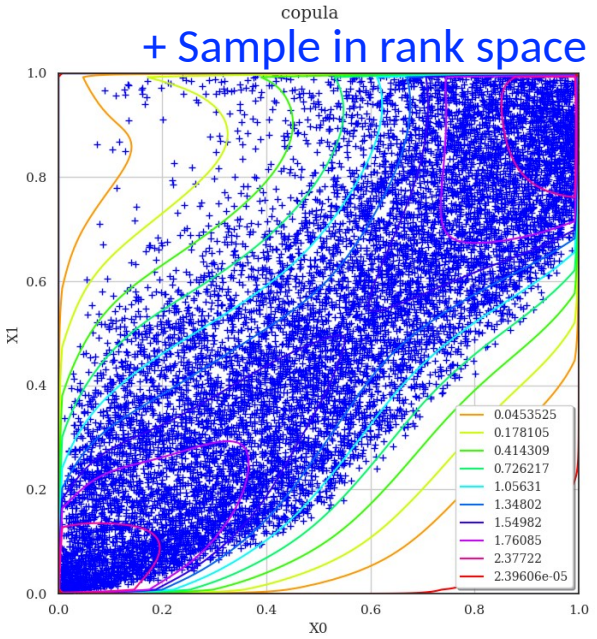
All days vs. critical days

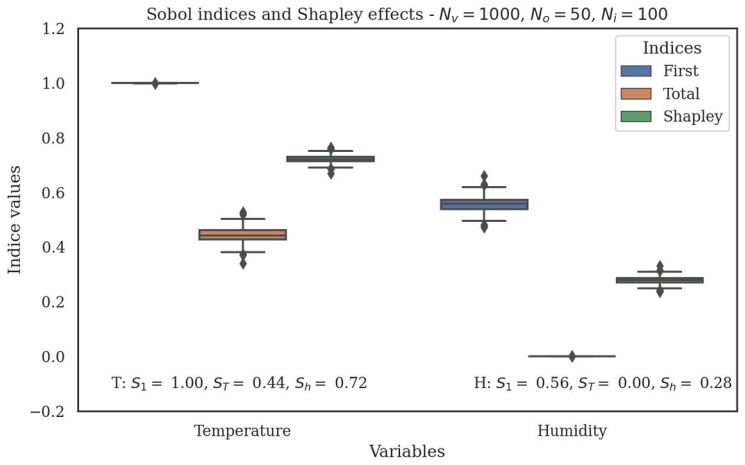


All days vs. critical days

All year

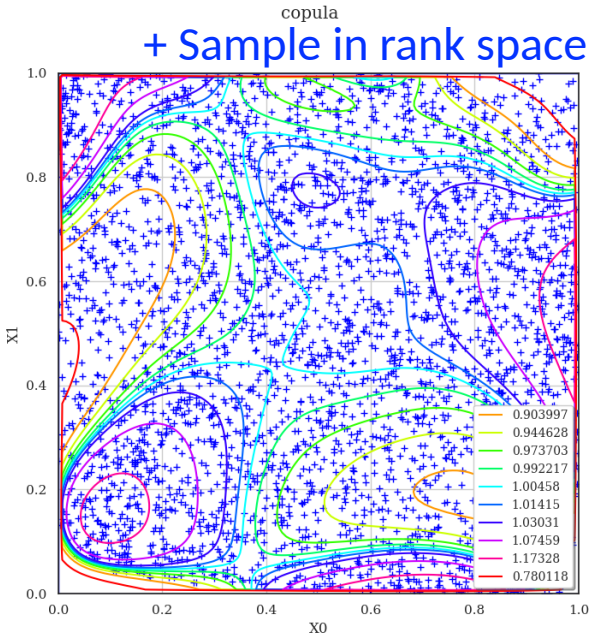
Correlation coefficients
Pearson: 0.77
Spearman: 0.81

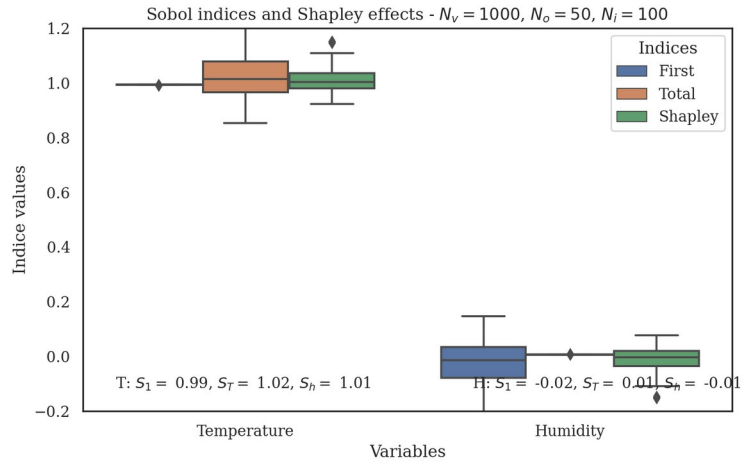




Critical days

Correlation coefficients:
Pearson : -0.048
Spearman : -0.018

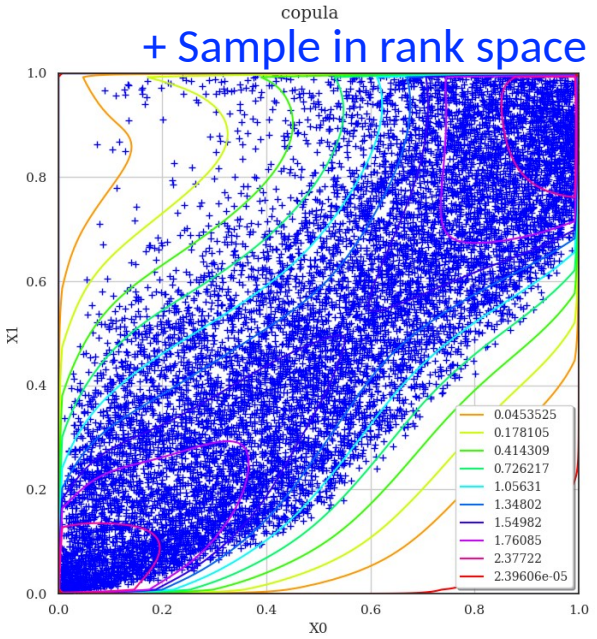




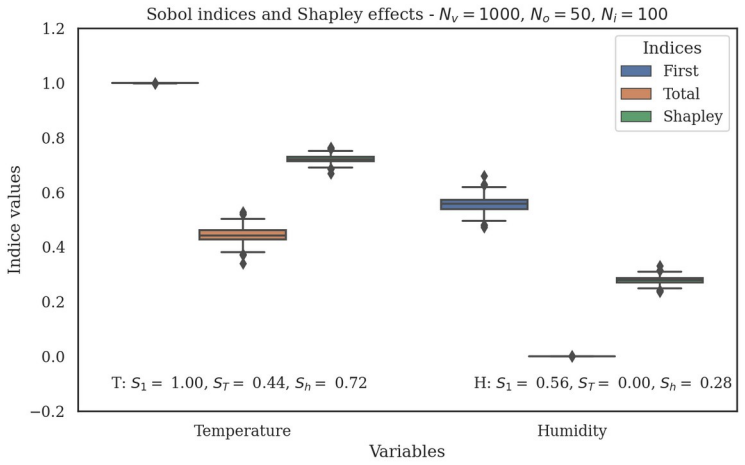
All days vs. critical days

All year

Correlation coefficients
Pearson: 0.77
Spearman: 0.81

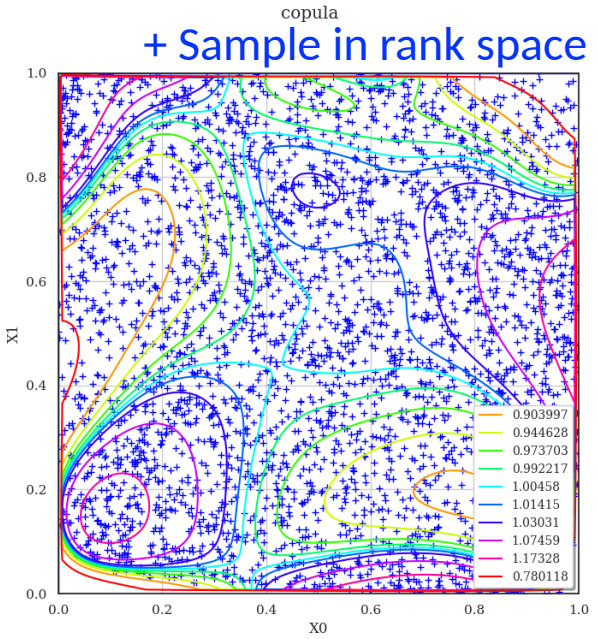


+ Sample in rank space

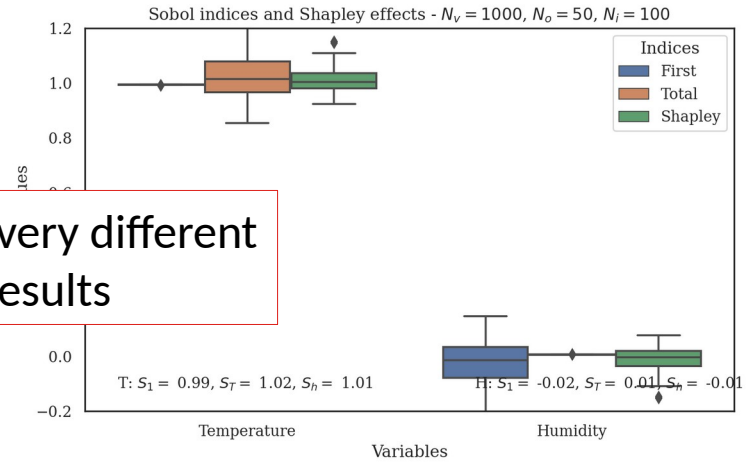


Critical days

Correlation coefficients:
Pearson : -0.048
Spearman : -0.018



+ Sample in rank space



Dependency structure very different
✉ Impacts sensitivity results

Conclusion and perspectives

Conclusion

- High temperature and humidity have a negative effect on performance
- Sensitivity of MTOW: Temperature predominant in its elementary influence but humidity also has a non negligeable influence in case of dependency
- Methodology put into place in order to add more input variables and outputs
  - → Other atmospheric variables: wind components, precipitation…
  - → Parameters of the aircraft: compression ratios, efficiencies in engine…

Thank you for your attention

Institut Supérieur de l'Aéronautique et de l'Espace

10, avenue Edouard Belin – BP 54032
31055 Toulouse Cedex 4 – France
T +33 5 61 33 80 80

www.isae-supaero.fr

Special thanks to

- Regis Lebrun for theoretical support
- Joseph Muré for help with the ot.shapley package

Some references

[1] V. Grewe, A. Gangoli Rao, T. Grönstedt, and et al., 2021. *Evaluating the climate impact of aviation emission scenarios towards the paris agreement including covid-19 effects*. *Nature Communication*, 12(3841)

[2] E. Coffel and R. Horton, 2015. *Climate Change and the Impact of Extreme Temperatures on Aviation*, Weather, Climate, and Society, 7(1):94-102 [3] Élodie Roux, 2005. *Pour une approche analytique de la dynamique du vol*. Phd Thesis (Ecole Nationale Supérieure de l'Aéronautique et de l'Espace, Toulouse).

[4] A Voldoire, D Saint-Martin, and S Sénési, 2019. *Evaluation of CMIP6 DECK experiments with CNRM- CM6-1*. 11:2177–2213.

[5] 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*. Technical report, Cambridge Univer- sity Press. In Press.

[6] Baudin, Michaël & Lebrun, Régis & Iooss, Bertrand & Popelin, Anne-Laure., 2015. *OpenTURNS: An Industrial Software for Uncertainty Quantification in Simulation*. 10.1007/978-3-319-11259-6_64-1.

[7] Sancetta, Alessio & Satchell, Stephen, 2004. *The Bernstein copula and its applications to modeling and approximations of multivariate distributions*. Econometric Theory. 2004. 20. 535-562. 10.1017/S026646660420305X.