# Recurrence Quantification Analysis of temperature time series from marine cumulus clouds during EUREC4A

Stanisław Król[1] Szymon Malinowski[1]

[1]University of Warsaw, Poland

European Geosciences Union, 2022

## Data

EUREC4A [1] campaing conducted in early 2020 was an experiment focused on studying cumulus clouds and coupling between clouds and marine atmospheric boundary layer.

# Data

Ultra Fast Thermometer, developed at the University of Warsaw, was mounted on the Twin-Otter aircraft, and gathered data during 7 flights. It is able to measure temperature at 20 kHz frequency, which translates to centimeter-scale spatial resolution. Using temperature and microphysical readings, segments containing information about cloud air were extracted and analysed further.

# Data

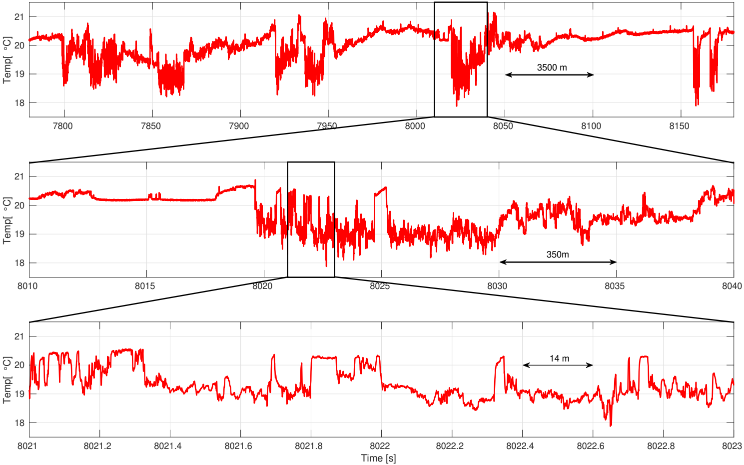


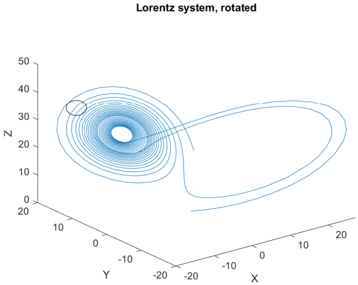

**Figure:** Sample readings

# Hypothesis

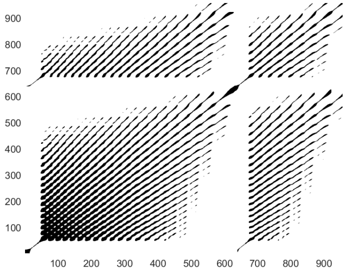
We believe that this data contains useful information about turbulent mixing of cloud air. We treat the cloud air as a non-linear, dynamical system. The proposed method of data analysis is recurrence plot (RP) method, and recurrence quantification analysis (RQA).

# Method

RP [2] is a tool used to visualise recurrencies in a dynamical system, as well as transitions and regions of different types of chaos. The data used in the analysis consists of temperature, TKE, and vertical velocity, all with 50 Hz frequency.




**(a)** Lorenz system




**(b)** RP of Lorenz system

# Method

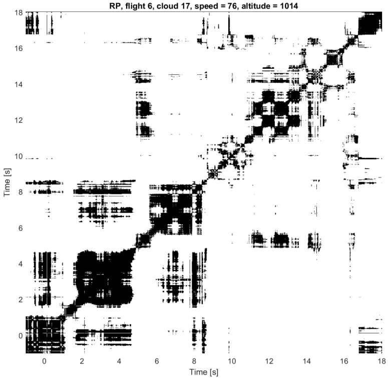
Recurrence is a crucial characteristic of dynamical systems. In the recurrence plot method, we study the recurrencies of vector $\vec{x}$ and construct a matrix $R_{ij}$:

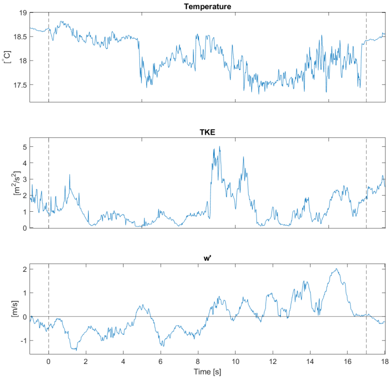
$$R_{i,j} = \Theta(\epsilon - ||\vec{x}_i - \vec{x}_j||).$$

Where $\Theta(\cdot)$ is the Heavyside function, and index $i$ denotes point in time series. Then we draw the plot of the matrix, colouring cells containing 1 black, and cells containing 0 white.
In this study we constructed a vector such that:

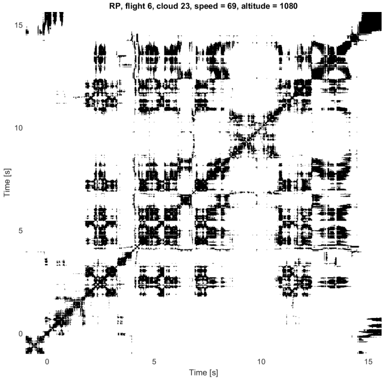
$$\vec{x} = [T, k, w'].$$

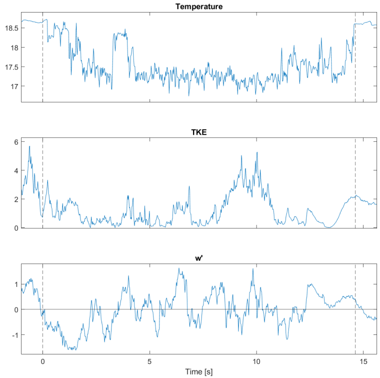
# Results


RP, flight 6, cloud 17, speed = 76, altitude = 1014
Time [s]
Time [s]


Temperature
[°C]
TKE
[m²/s²]
w'
[m/s]
Time [s]

# Results


RP, flight 6, cloud 23, speed = 69, altitude = 1080
Time [s]
Time [s]
0
5
10
15
0
5
10
15


Temperature
18.5
18
17.5
17
TKE
6
4
2
0
w'
1
0
-1
0
5
10
15
Time [s]

# Results

The two cases above are the case studies selected from a large number of observed clouds. The first case is the cloud penetrated from the leeward side. It exhibits an erratic behaviour of temperature near the windward side, an increase of TKE in the middle, and oscilating vertical wind variable component. The second case is the cloud penetrated from the side, in which the temperature has an erratic behaviour during the whole penetration, except for a short increase indicating the measurement of the temperature of entrained environmental air. The TKE and vertical wind component are somewhat similar to the previous case.

# Results

The RPs serve a diagnostic purpose, and in this case we focus on the white bands indicate a change in the system, vertical or diagonal black lines indicating a rather constant/laminar state and closed loops indicating oscilations. We can see that during the penetration of the first cloud, the system goes through a series of transitions through one state to another, and in the second case, the system changes it's state but it has more fractal-like and oscilating structure.

# Results

Recurrence Quantification Analysis is a method of data analysis which quantifies structures (black lines) found in the recurrence plot. We employ its time-dependent version using 2 kHz temperature time series as a 1D vector. For each 2000 points we create a RP and then perform RQA and then move by an jump and repeat the procedure. Therefore we obtain a time dependence of certain quantities of RQA of temperature time series.

# Results

Quantities of interest:

1. Determinism (DET)

$$DET = \frac{\Sigma_{l=l_{min}}^{N} lP(l)}{\Sigma_{l=1}^{N} lP(l)}$$

2. Average diagonal line length (L)

$$L = \frac{\Sigma_{l=l_{min}}^{N} lP(l)}{\Sigma_{l=l_{min}}^{N} P(l)}$$

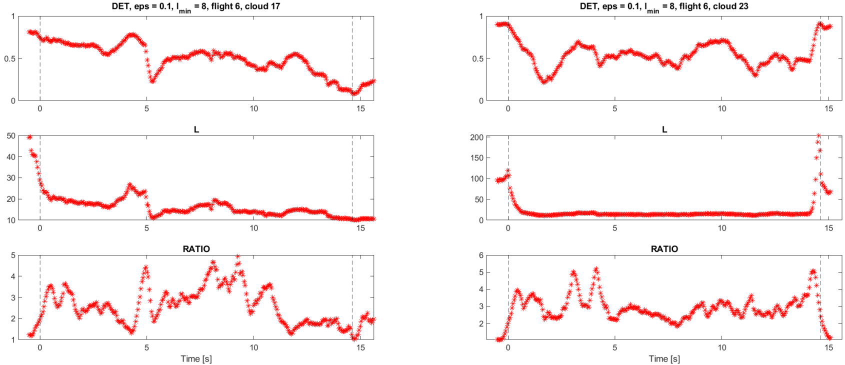
3. RATIO

$$RATIO = \frac{DET}{\frac{\Sigma_{i,j=1}^{N} R_{i,j}}{N^2}}$$

The value $l_{min}$ is chosen using space-time separation plot [3].

# Results

Time-dependent RQA for temperature readings:



## Results

The value DET which is a rough estimate of chaos in the system decreases in the first case, and in the second case remains constant with some oscilations. In the first case this means that the system goes through more ordered state to the less ordered state, and in the second case its state remains relatively constant with some transitions.

## Acknowledgements

We acknowledge funding by Poland's National Science Centre grant no. UMO-2018/30/M/ST10/00674.

Bibliography & further reading:

1. *EUREC4A*, B. Stevens et al., Earth Syst. Sci. Data, 13, 4067–4119, 2021
2. *Recurrence plots [...]*, N. Marwan et al., Phys. Rep., 438, 5–6, 237-329, 2007
3. *Distinguishing between [...*], A. Provenzale et al., Physica D, 58, 31, 1992.