Turbulent mixing in marine cumulus clouds - experimental data analysis

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Motivation

Clouds are very important objects present in the atmosphere. Their representation is regarded as the largest source of uncertainty in weather and climate models.

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This study is concerned with marine cumulus clouds. They are convective phenomena, and their size (both vertical and horizontal) is of the order of hundreds of meters.

Cloud processes

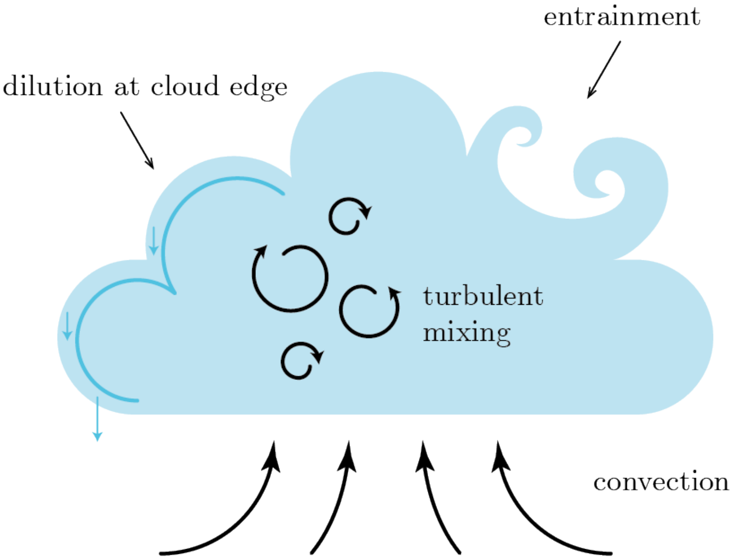

Figure: A selection of cloud processes

Cloud turbulence

Turbulent mixing affects cloud dynamics, and consequently, larger scale processes. Therefore studying cloud turbulence might give a solution to better numerical schemes.

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The starting point in the study of turbulence in terms of its statistical properties is the theory of homogeneous and isotropic turbulence (HIT) developed by Kolmogorov.

A useful concept for understanding the dynamics of a turbulent flow is the concept of an energy cascade.

Energy cascade

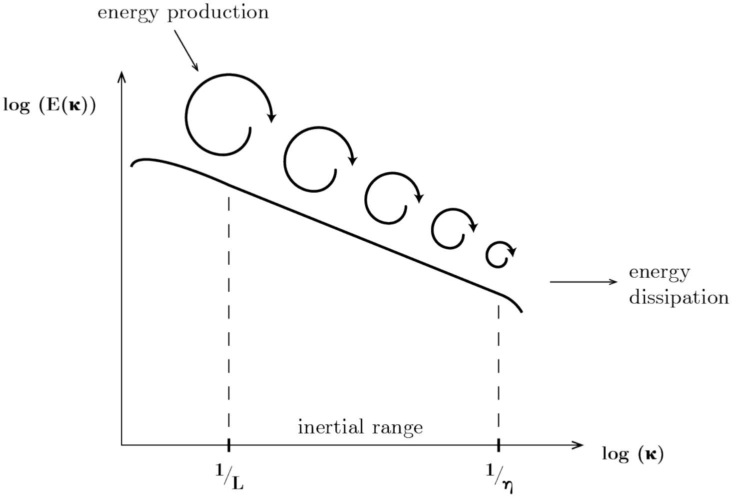

Figure: A schematic of an energy cascade

ε

In this case ε is regarded as an energy flux going from the largest to the smallest scales. Several methods of obtaining ε from lower-resolution data exist, e.g.:

$$E(\kappa) = C_K \varepsilon^{2/3} \kappa^{-5/3}, \tag{1}$$

$$D_{11}(r) = C_{11} \varepsilon^{2/3} r^{2/3}. \tag{2}$$

Also, ε is connected to other quantities via Taylor's relation:

$$\varepsilon = C_\varepsilon \frac{u'^{3/2}}{L}, \tag{3}$$

Deviations from HIT

Two deviations from the HIT theory are considered in this work:

1. Non-equilibrium turbulence
2. Anisotropic turbulence

Non-equilibrium turbulence

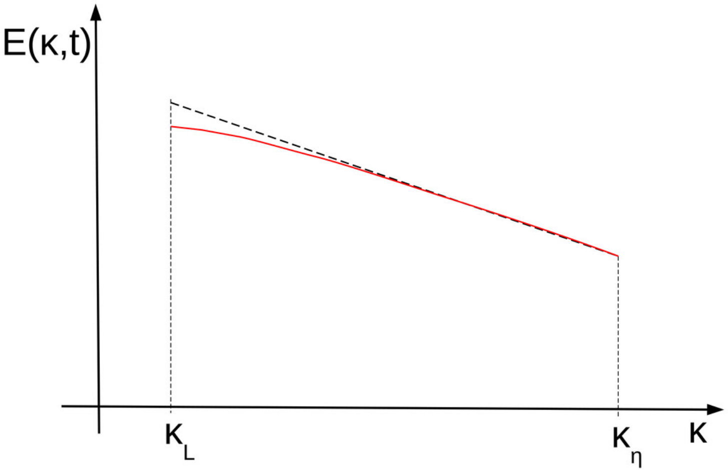

Figure: A deviation from the -5/3 law

Non-equilibrium turbulence

$$E(\kappa) = C_K \varepsilon^{2/3} \kappa^{-5/3} \quad E(\kappa, t) = \overline{E}(\kappa, t) + \widetilde{E}(\kappa, t) \tag{4}$$

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$$\frac{C_\varepsilon}{\overline{C_\varepsilon}} \approx \left(1 + \frac{\widetilde{k}}{\overline{k}}\right) = \left(\frac{\mathrm{Re}_{\lambda 0}}{\mathrm{Re}_\lambda}\right)^{15/14} \rightarrow C_\varepsilon \approx \frac{1}{\mathrm{Re}_\lambda} \tag{6}$$

The derivation was done in Bos 2017.

Anisotropic turbulence - approach

The study of anisotropy includes the analysis of the ratio of magnitude of fluctuations in different directions e.g.:

$$A_u = \sqrt{\frac{2\langle w'^2 \rangle}{\langle u'^2 \rangle + \langle v'^2 \rangle}}, \tag{7}$$

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as well as the ratio of TKE dissipation rates:

$$A_\varepsilon = \frac{2\varepsilon_W}{\varepsilon_U + \varepsilon_V}. \tag{8}$$

Anisotropic turbulence - approach

Another way to study anisotropy is the analysis of the invariants of the *normalised anisotropic tensor*:

$$a_{ij} = \frac{\overline{u_i' u_j'}}{2k} - \frac{\delta_{ij}}{3}. \tag{9}$$

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$$I = \lambda_1 + \lambda_2 + \lambda_3 = 0$$

$$II = \lambda_1^2 + \lambda_1 \lambda_2 + \lambda_2^2$$

$$III = -\lambda_1 \lambda_2 (\lambda_1 + \lambda_2)$$

Anisotropic turbulence

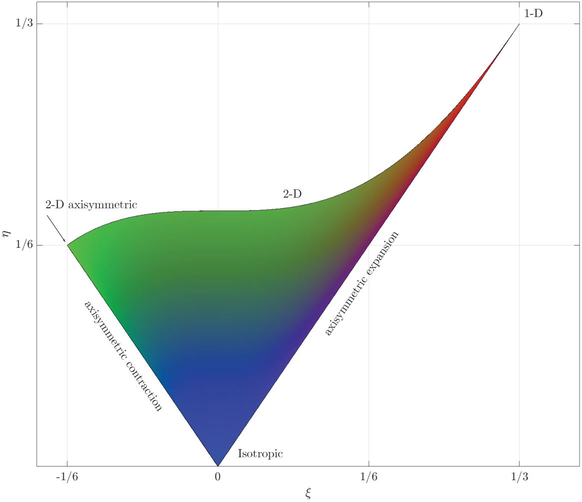

Figure: Turbulence triangle

A different approach

In this work, the clouds and cloud turbulence were also analysed based on a method that stems from the analysis of dynamical systems, namely Recurrence Plot and Recurrence Quantification Analysis.

Recurrence plot - definition

Let's define a vector $\vec{x}$ which represents a state of a system.

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We can define a we define a recurrence matrix:

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

where ϵ is called a recurrence threshold, $\vec{x}_i$ is a vector at time i, and $\Theta(\cdot)$ is the Heavyside function, and $||\cdot||$ is a norm (in this case an L-2 norm).

Recurrence plot - example

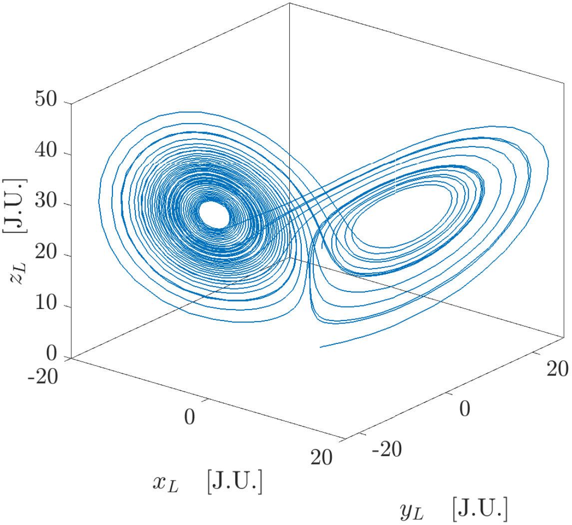


Figure: Lorenz system

Recurrence plot - example

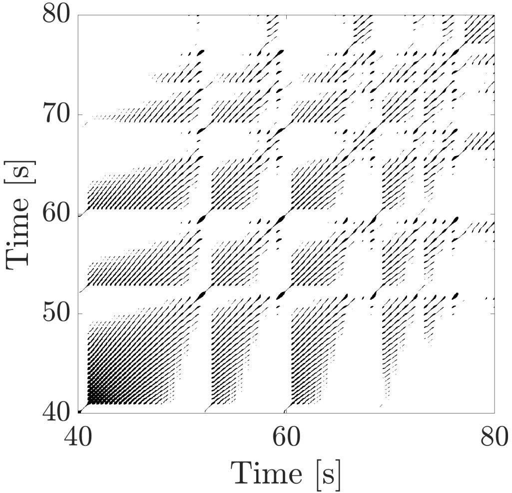


Figure: Recurrence Plot of the Lorenz system

Observation of RPs

1. Diagonal lines (parallel)
   -> the evolution of states is similar at different times, the process could be deterministic
2. White bands
   -> nonstationarity, some states are rare or far from the normal, transitions may have occurred
3. Periodic patterns
   -> cyclicities in the process

Observation of RPs

1. Vertical and horizontal lines/clusters
   -> some states do not change or change slowly for some time, indication for laminar states
2. Single isolated points
   -> heavy fluctuation in the process
3. Homogeneity:
   -> the process is stationary
4. Fading to the upper left and lower right corners:
   -> nonstationarity; the process contains a trend or drift

RQA

Recurrence quantification analysis:

1. Recurrence Rate (RR)

$$RR = \frac{\sum_{i,j=1}^{N} R_{i,j}}{N^2}$$

2. Determinism (DET)

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

3. Laminarity (LAM)

$$LAM = \frac{\sum_{v=v_{min}}^{N} vP(v)}{\sum_{v=1}^{N} vP(v)}$$

RQA

Recurrence quantification analysis:

1. Average diagonal line length (L)

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

2. Trapping time (TT)

$$TT = \frac{\Sigma_{v=v_{min}}^{N} vP(v)}{\Sigma_{v=v_{min}}^{N} P(v)}$$

3. Ratio (RATIO)

$$RATIO = \frac{DET}{RR}$$

RQA - examples

Table: Values of selected quantities in the RQA for different systems

Quant.	RN	Lorenz	Period	Brown
l_{min}, v_{min}	2	10	52	20
RR	0,191	0,079	0,110	0,217
DET	0,346	0,894	0,398	0,581
LAM	0,362	0,403	0	0,702
LL	2,23	30,53	186,54	37,07
TT	2,30	12,30	0	41,54
$RATIO$	1,81	11,21	3,66	2,68

Data

The data used in this study come from the measurements done by the Twin-Otter aircraft during EUREC4A campaign.

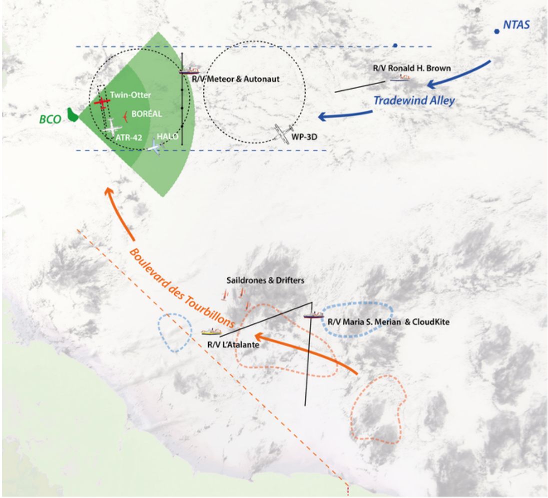


Figure: A schematic showing the overview of the campaign

Data

Figure: A cloud

Data - problems

During the analysis, several problems with the data were identified.

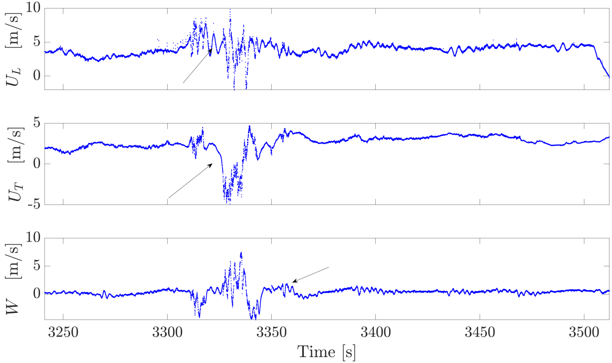


Figure: An image showing example problems with the data

Data - conclusion

Table: Metadata. N_o – number of periods, ΣT_o – length of periods in minutes, N_c – number of clouds.

Flight	Date	N_o	ΣT_o [min]	N_c
330	24.01	8	58	22
331	24.01	3	20	0
334	28.01	5	35	4
336	30.01	5	25	4
341	5.02	1	8	0
342	6.02	4	21	0
343	7.02	2	22	0
344	7.02	1	10	0
349	11.02	5	38	19

Data - example

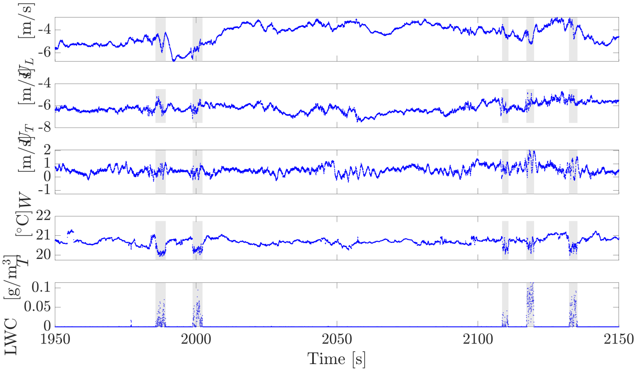


Figure: An example time series showing three components of wind velocity, temperature, and liquid water content.

Input parameters

First, in order to calculate the fluctuating part of velocity (u') via Reynolds decomposition, we need to calculate the mean over a certain window, τ_d.

We also need to choose a window over which the statistics ($< \cdot >$,ε, etc.) are calculated, τ_a. Ideally, this window should be several times larger than τ_d.

Results - turbulence

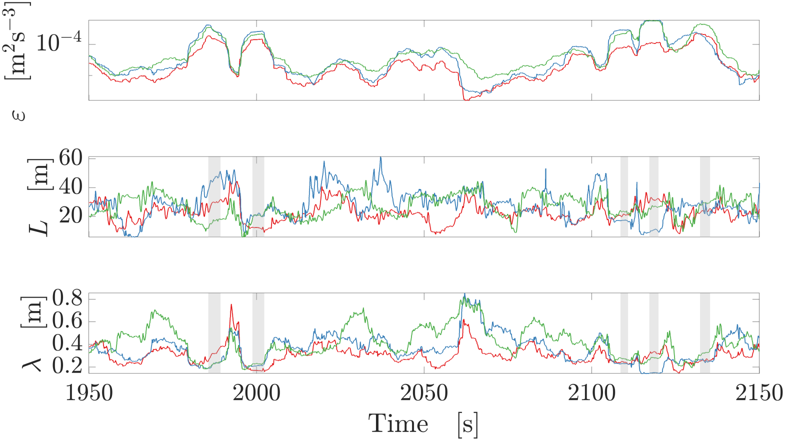


Figure: A time series of basic turbulence quantities.

Results - turbulence

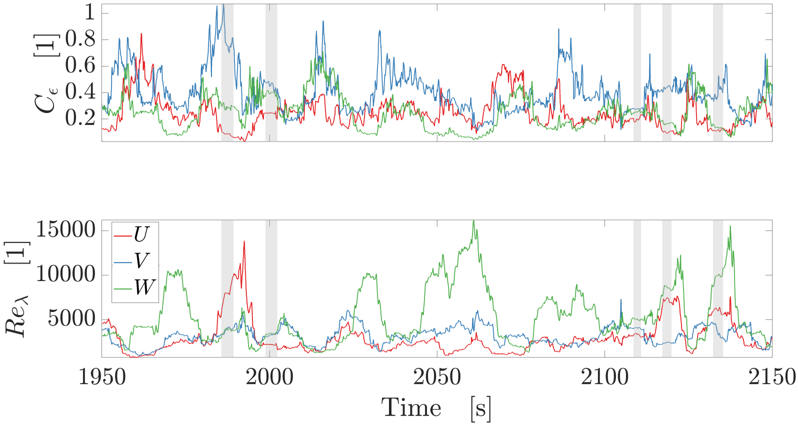


Figure: A time series of other turbulence quantities.

Results - nonequilibrium turbulence

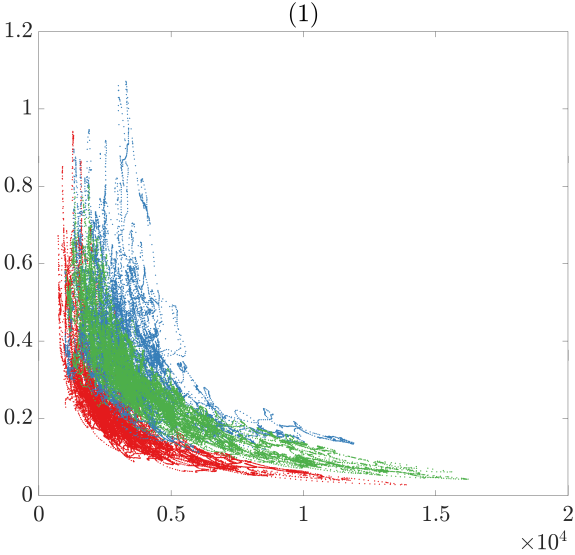


Figure: A plot of C_ε vs Re_λ.

Results - anisotropic turbulence

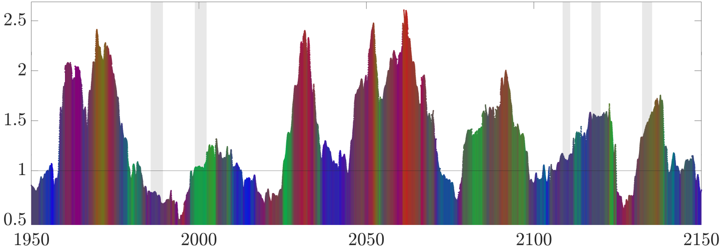


Figure: Time series of A_v.

Time-dependent RQA

In this analysis, a time-dependent RQA was performed. That is, a matrix based only on a portion of the data was constructed, and then the standard RQA was performed. This way, time series of the aforementioned parameters were obtained.

In this case, a following vector was constructed:

$$\vec{x} = [T, w', k]. \tag{10}$$

Results - RQA

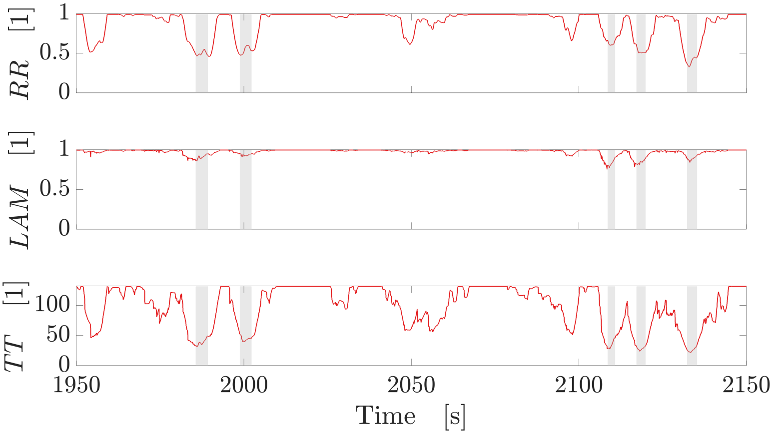
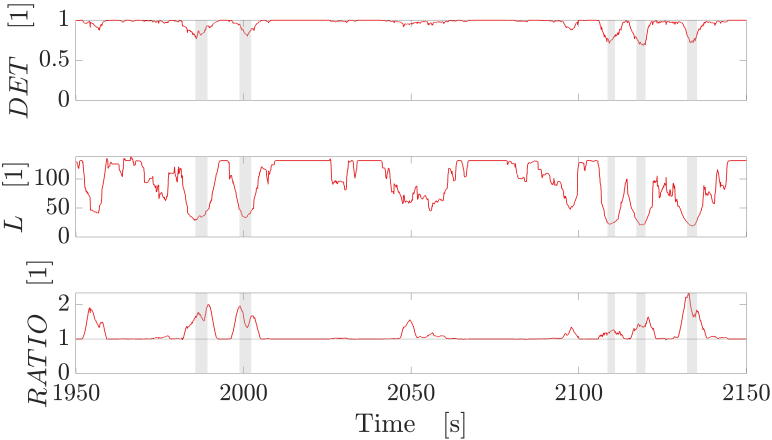


Figure: A time series of selected quantities in the RQA.

Results - RQA



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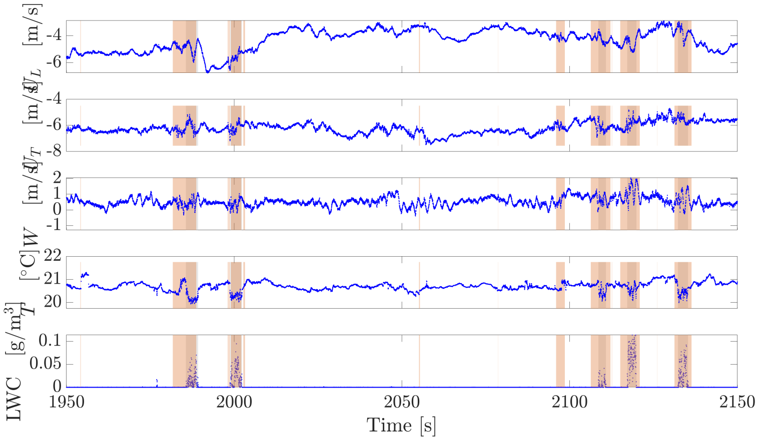

Figure: An example time series with the LAM mask denoted by orange rectangles

Results

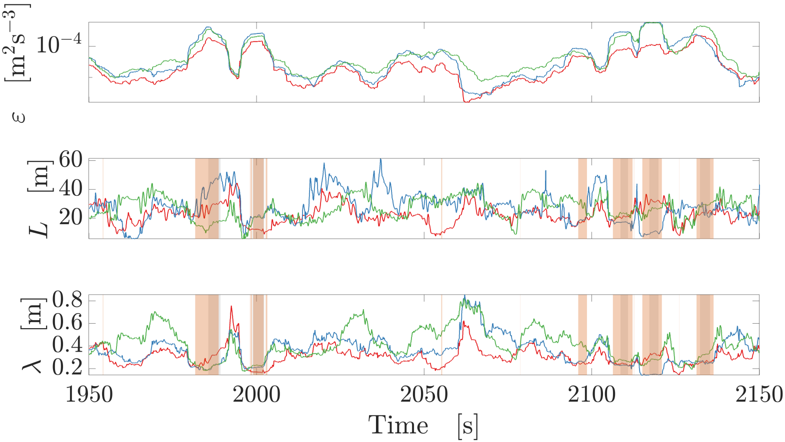

Figure: An example time series of turbulence quantities with the LAM mask denoted by orange rectangles

Results

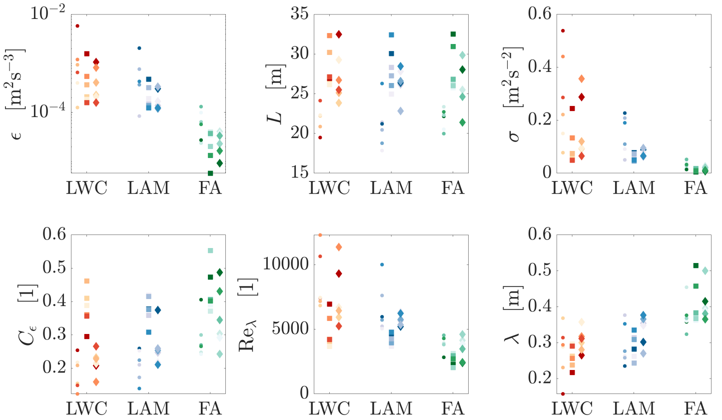

Figure: Values of different quantities averaged with respect to 3 masks

Results

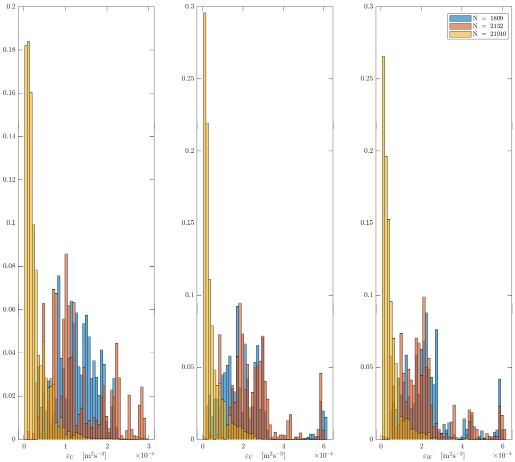

Figure: Histograms of ε for different directions and masks

Conclusion

1. An analysis of turbulence in and around cumulus clouds was performed.
2. Departure from HIT was observed. In my opinion, we need to look at cloud turbulence in terms of extended theories.
3. An RQA was done for the airborne time series.
4. A method to distinguish turbulent and non-turbulent segments was proposed. It has its advantages.

Outlook

This framework should be tested against a bigger dataset, but we are still waiting for the data.

A more in-depth analysis of parameters was performed for the PhD, but there are still possibilities to do more things with the RQA.

Literature

The literature and is available at BIP UW > DOKTORATY > Stanisław Król, or upon request.

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Thank you for your attention.