High-resolution temperature profiling in the LACIS-T wind tunel and the Pi Chamber

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Motivation

- thermal characterization of both facilities;
- Improve strategies for future experiments, instrumentation positioning;
- only a comprehensive understanding of full spectrum of scales analyses can effectively link together different phenomena;

Ultrafast Thermometer (UFT)

UFT-2A (left) and UFT-2B (right)

- 1992 – prototype, ~ 50 µm thick thermocouple
- 1997 – UFT, resistive platinum-coated tungsten wire, 2.5 µm thick, 5 mm long, ~50 Ω resistance, and time constant ~10^{-4} s

UFT-M (POST, 2007), UFT-2-0 (ACORES, 2017), UFT-2A and UFT-2B (EUREC^{4}A, 2020)

The current versions of UFT, UFT-2A and UFT-2B, utilize 3 mm long wire spanned on an industry miniature wire probes by DANTEC®

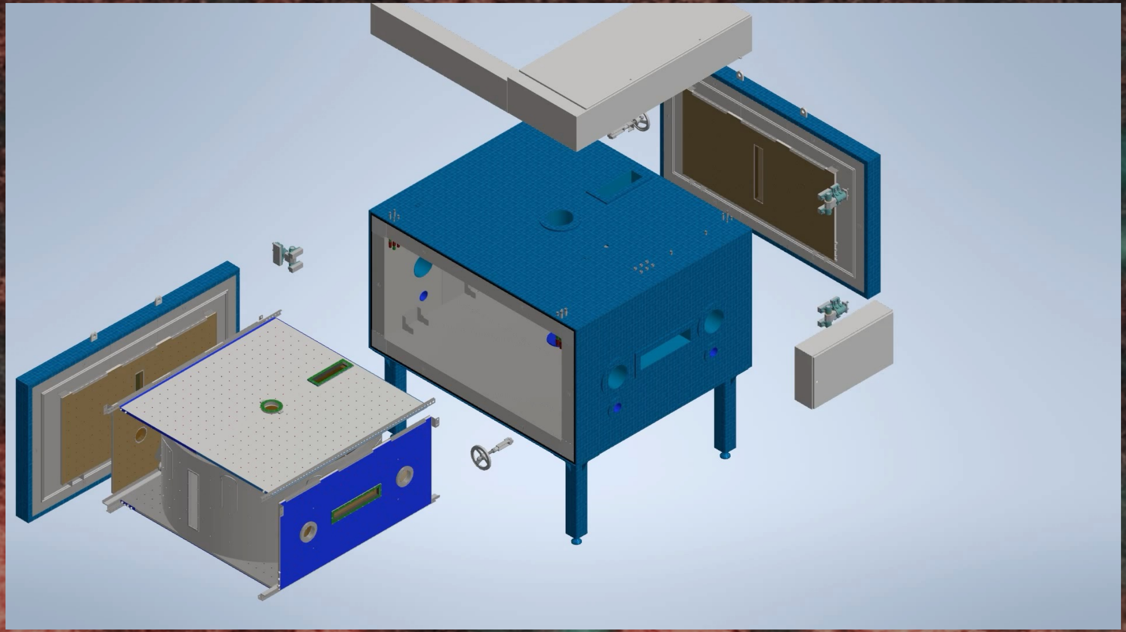
Haman, K. E., *et al.*, (1997), Kumala, W., *et al.*, (2013)

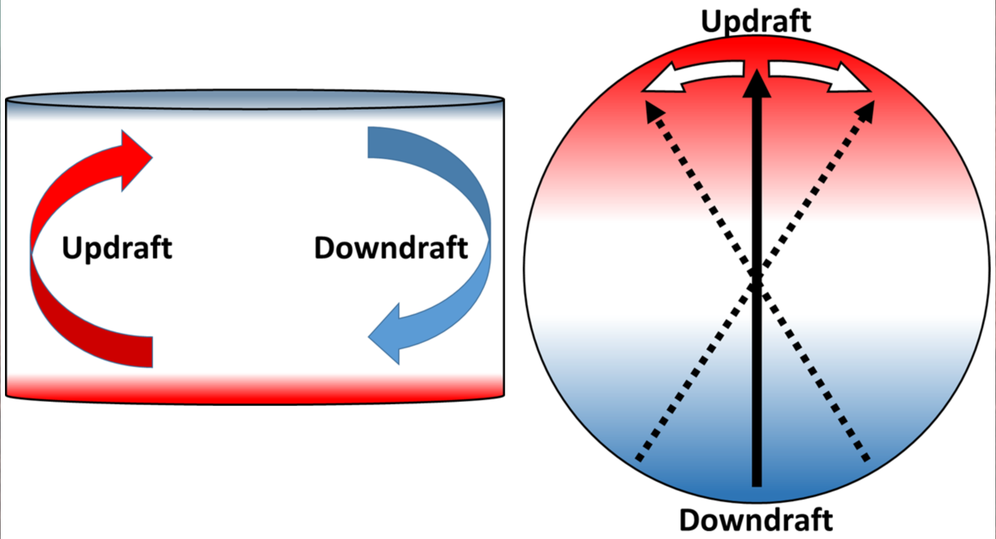
Part I
the Pi Chamber

Setup

- reproducible and controlled measurements across a wide range of temporal scales (minutes to days)
- operates in two modes (pressure reduction and Rayleigh-Bénard convection)

Chang, K., *et al.*, (2016)



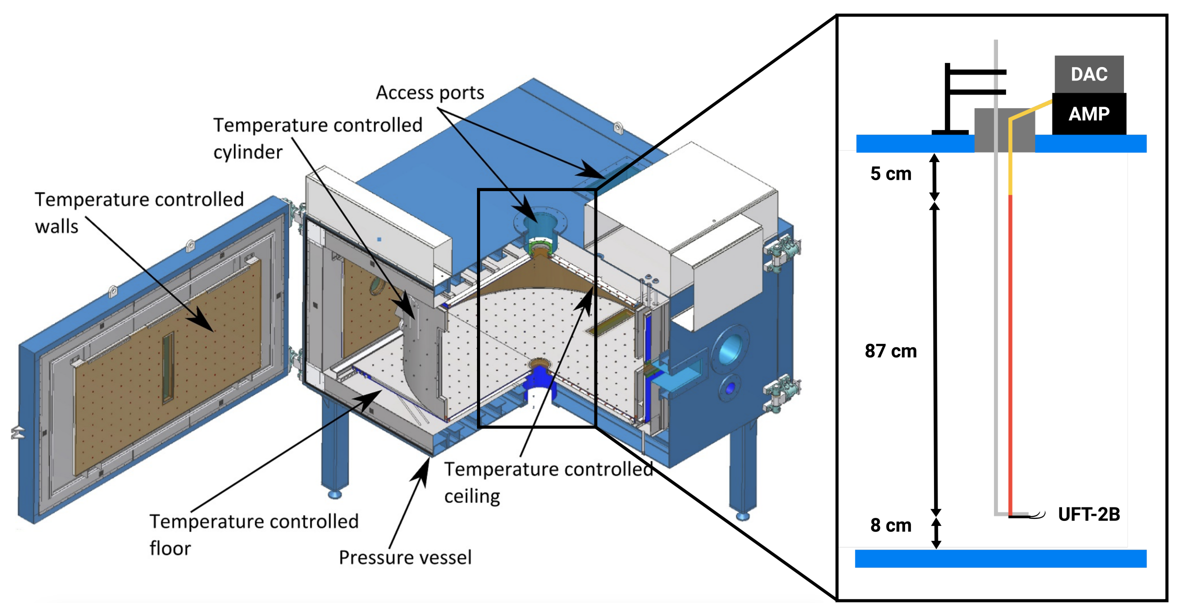


- The established large-scale circulation (LSC) period (single roll) for temperature difference $\Delta T = 12$ K, was approximated to $\tau_{12} \approx 72$ s (moist convection with mixing ratio of 7.55 g kg^{-1}).

Anderson, J. C., *et al.*, (2021)

Strategy

- high resolution (2 kHz) temperature time series at selected locations in a vertical profile near the axis of the chamber
- investigation under three ΔT: 10 K, 15 K, and 20 K at Rayleigh number $Ra \sim 10^9$ and Prandtl number $Pr \approx 0.7$



Experiment	Boundaries type	ΔT [K]	h [cm]	t [min]	Ra [$\times 10^9$]
V10-S-L	smooth	10	irregular	19	1.1
V10-S	smooth	10	8–95	3	1.1
V15-S-L	smooth	15	irregular	19	1.6
V15-S	smooth	15	8–95	3	1.6
V20-S-L	smooth	20	irregular	19	2.1
V20-S	smooth	20	8–95	3	2.1
V20-R	rough	20	8–95	3	2.1

The irregular positions are: 8, 14, 26, 35, 50, 65, 74, 86, 95 [cm].

- variable measurement time (3 min or 19 min)
- less emphasized aspect–the surface topography, i.e. longitudinal stripes on the floor and ceiling (aluminum bars, 4 cm wide and 1.4 cm high, separated by 17 cm intervals)

Strategy

Experiment	Boundaries type	ΔT [K]	h [cm]	t [min]	Ra [$\times 10^9$]
V10-S-L	smooth	10	irregular	19	1.1
V10-S	smooth	10	8–95	3	1.1
V15-S-L	smooth	15	irregular	19	1.6
V15-S	smooth	15	8–95	3	1.6
V20-S-L	smooth	20	irregular	19	2.1
V20-S	smooth	20	8–95	3	2.1
V20-R	rough	20	8–95	3	2.1

The irregular positions are: 8, 14, 26, 35, 50, 65, 74, 86, 95 [cm].

Experiments' name explanation:

V20-S-L

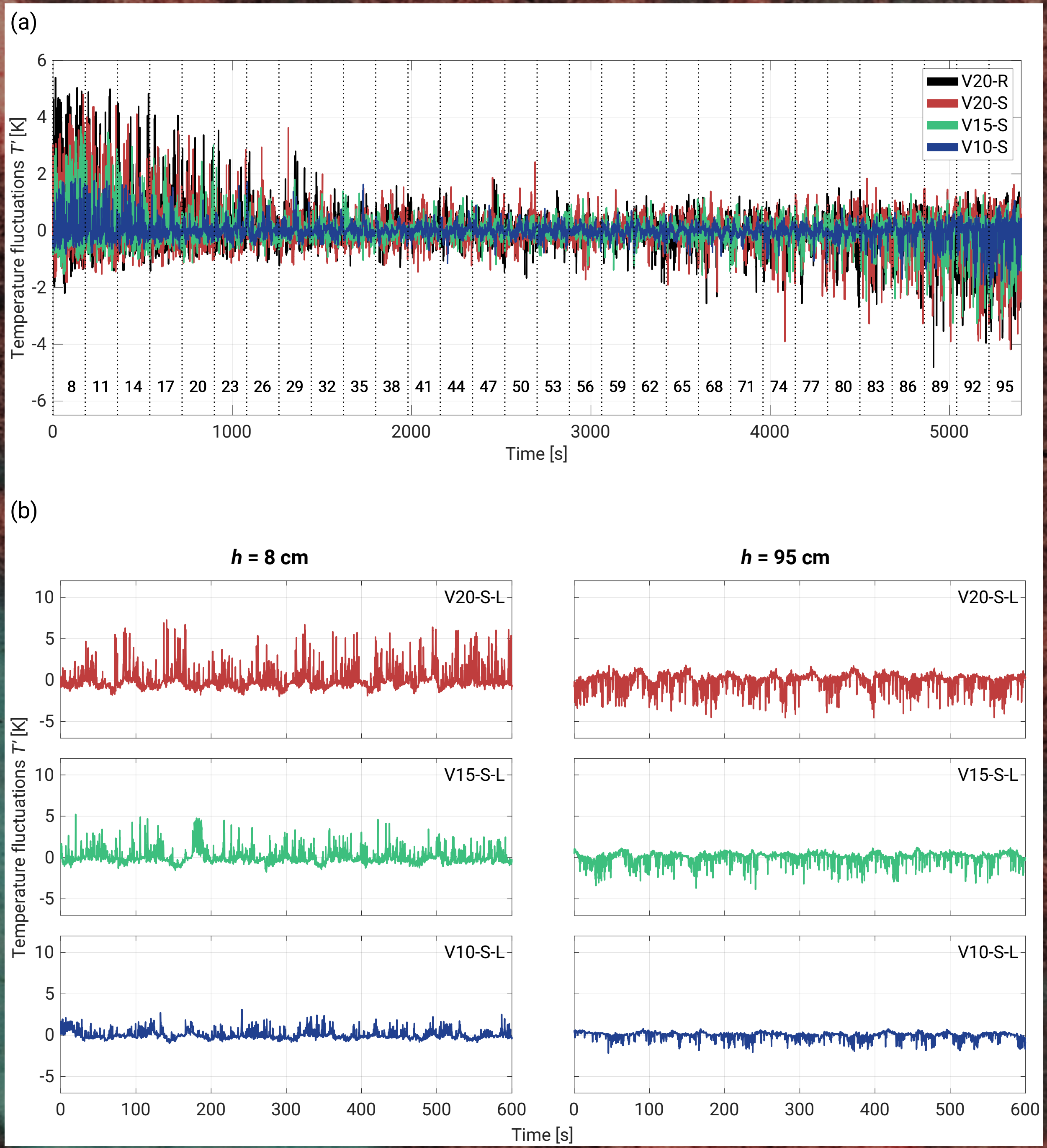
V – vertical profiling

20 – ΔT

S – type of boundaries (S for smooth and R for rough)

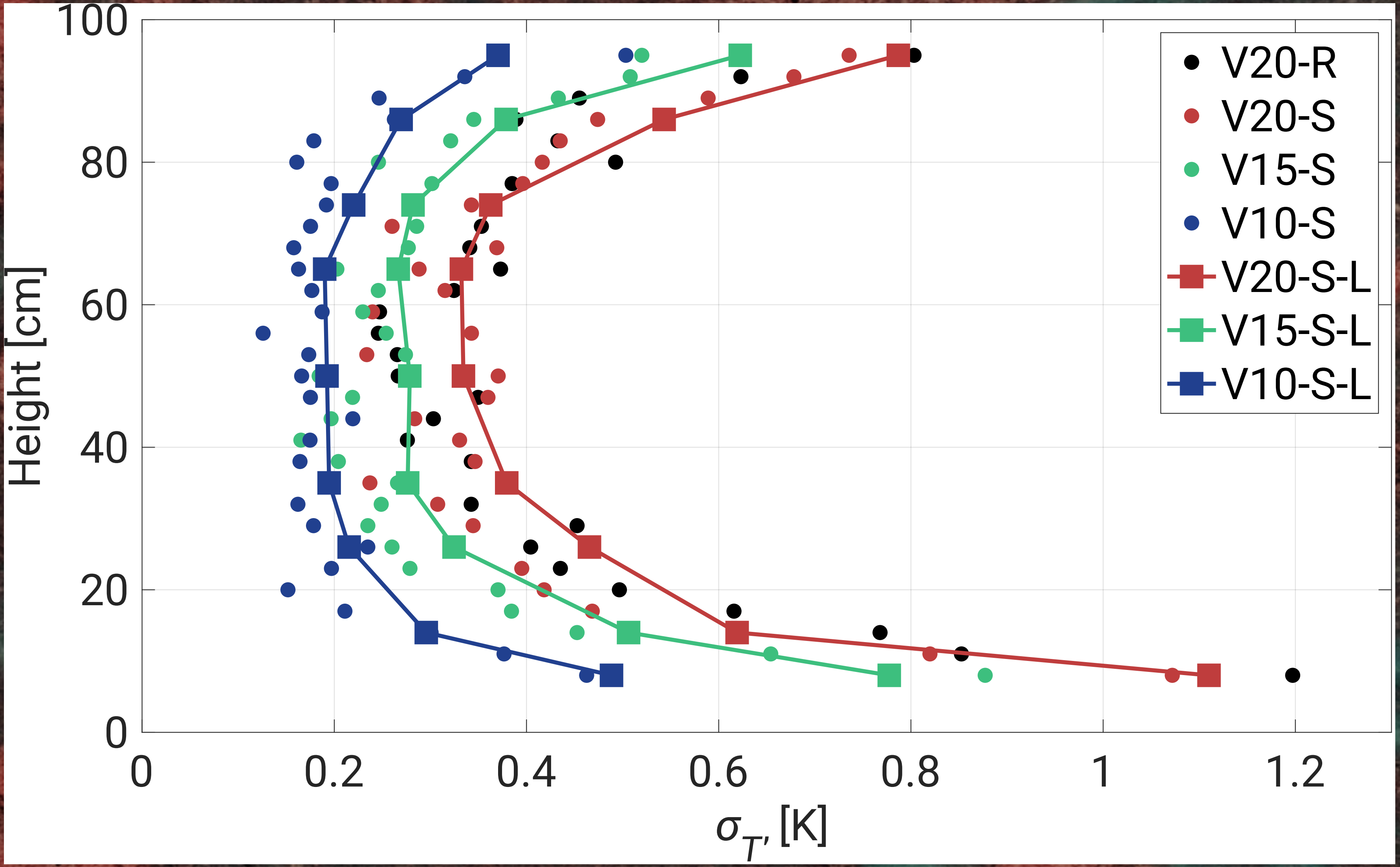
L – 19 min measurement time

Results

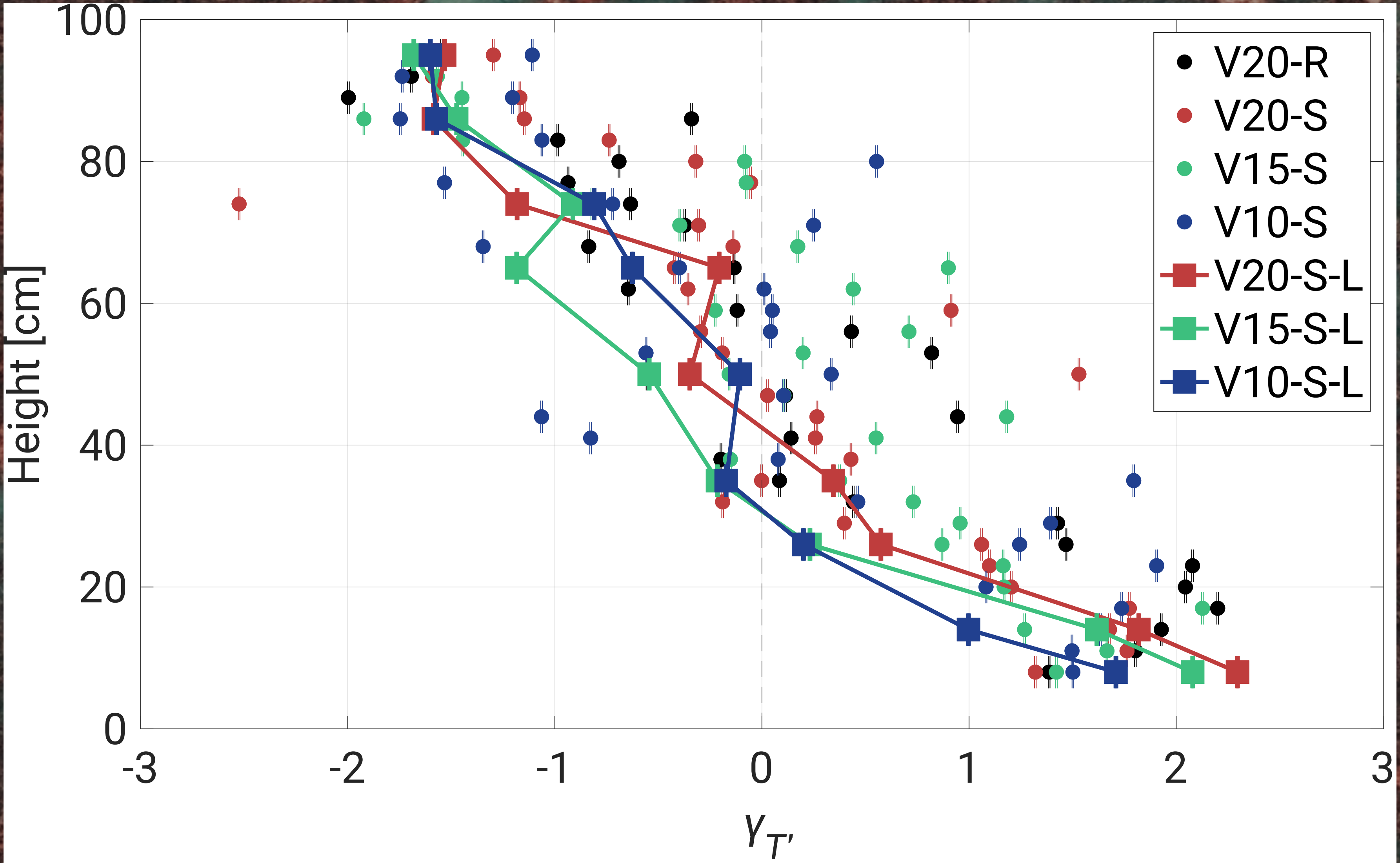


(a)
V20-R
V20-S
V15-S
V10-S
Temperature fluctuations T' [K]
8
11
14
17
20
23
26
29
32
35
38
41
44
47
50
53
56
59
62
65
68
71
74
77
80
83
86
89
92
95
Time [s]
(b)
h = 8 cm
h = 95 cm
V20-S-L
V15-S-L
V10-S-L
Temperature fluctuations T' [K]
Time [s]

Standard deviation



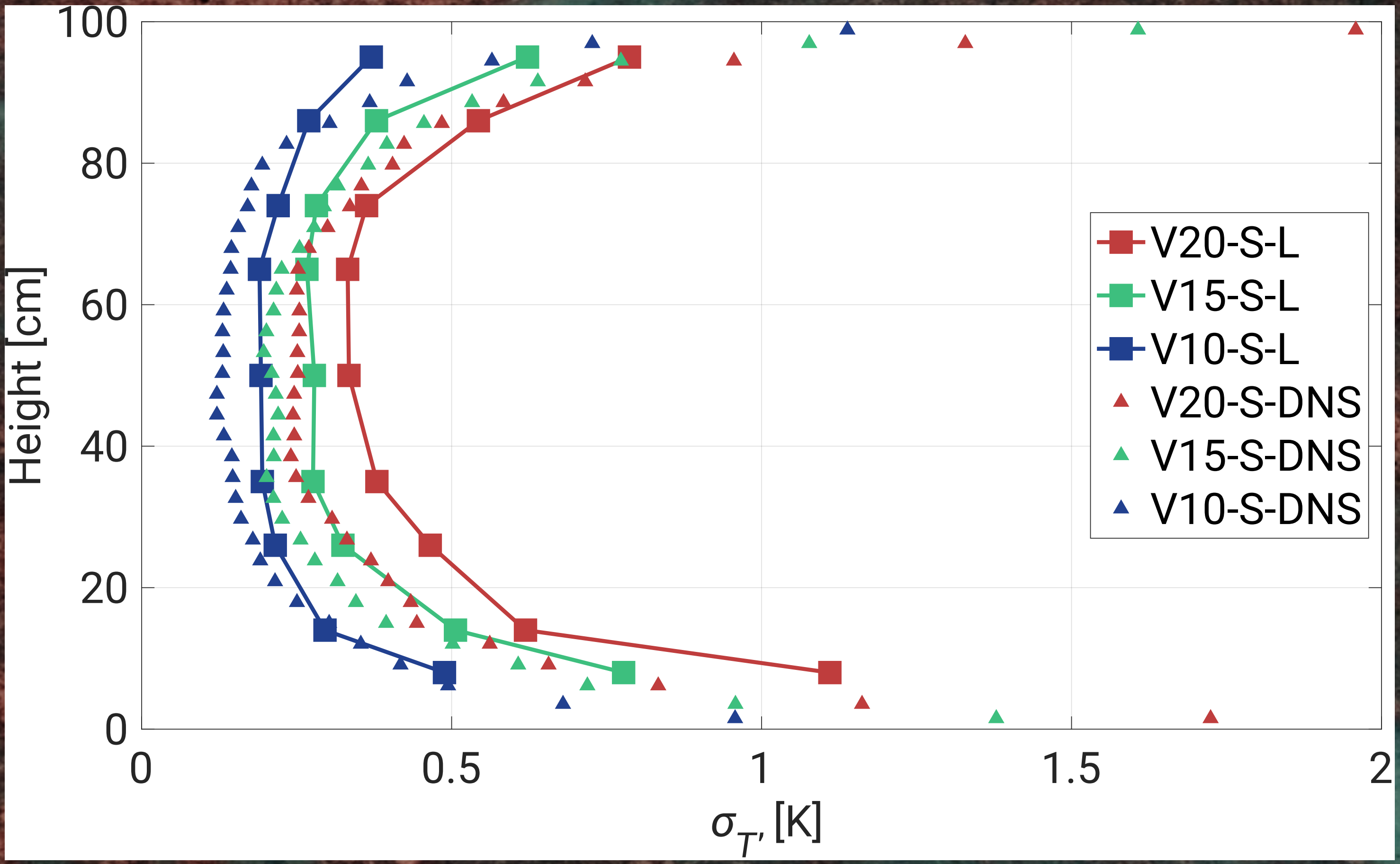
Skewness



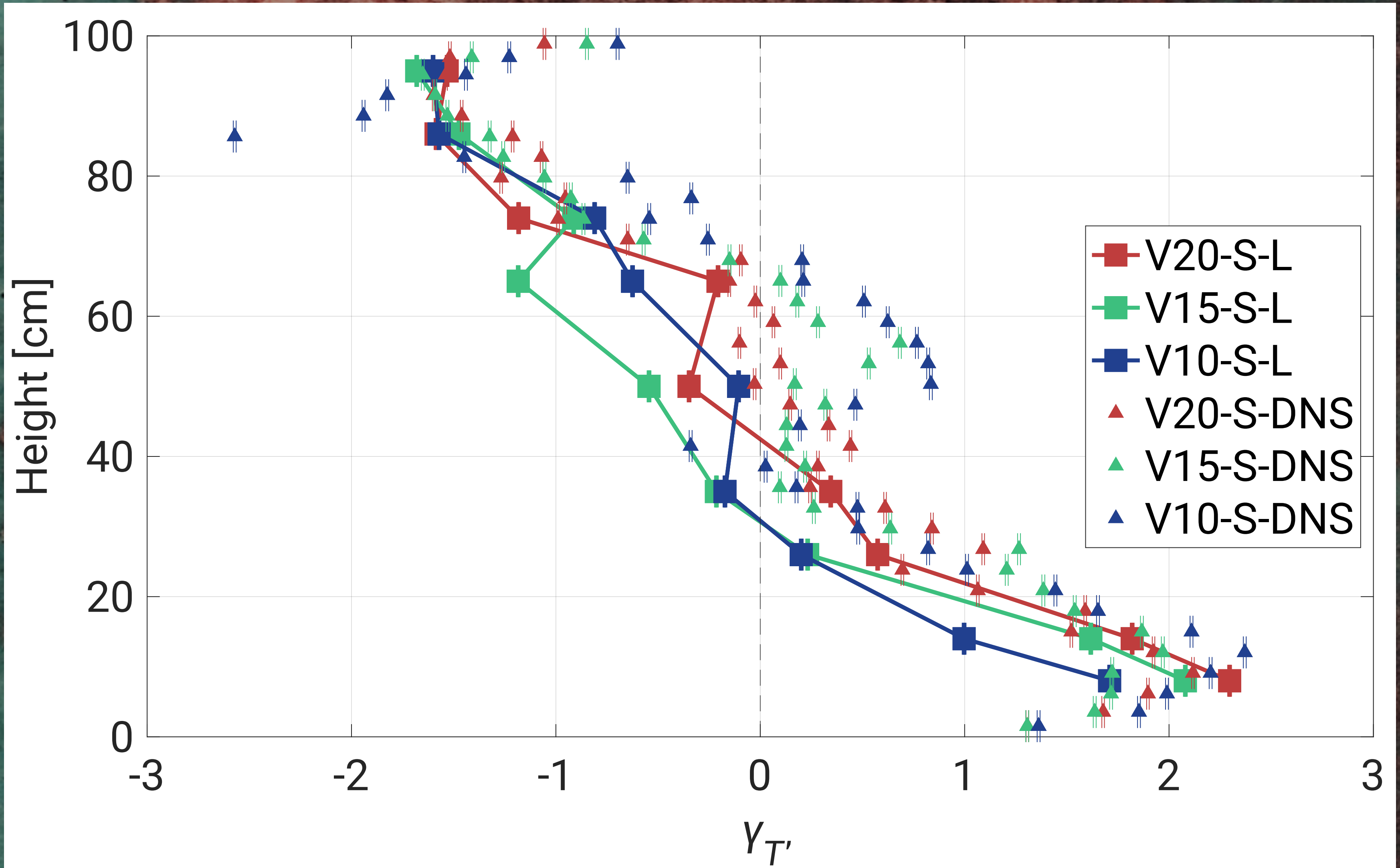
100
80
60
40
20
0
Height [cm]
-3
-2
-1
0
1
2
3
$\gamma_{T'}$
V20-R
V20-S
V15-S
V10-S
V20-S-L
V15-S-L
V10-S-L

DNS vs experiment – standard deviation

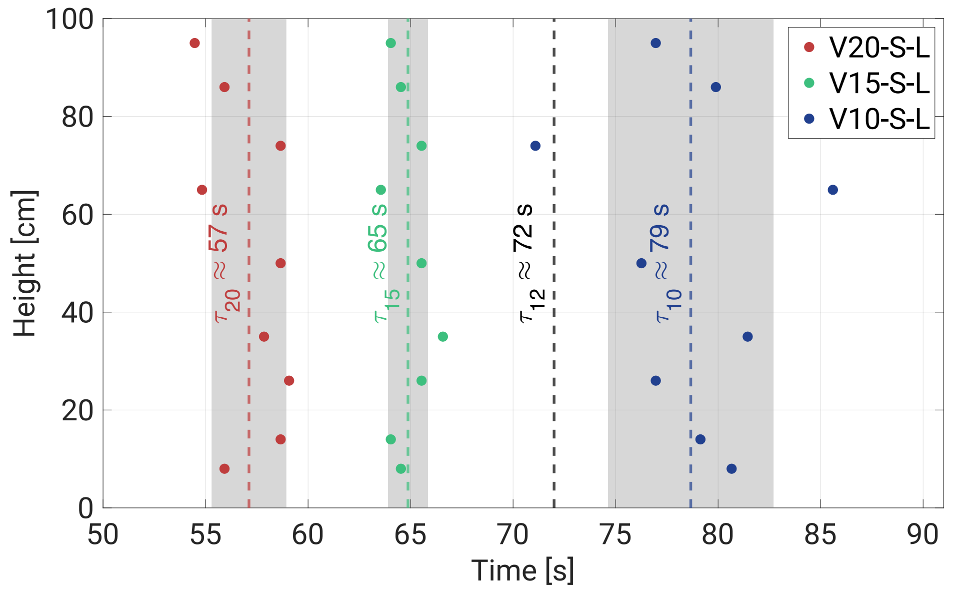
- Cloud Model 1 (CM1) (Bryan and Fritsch, (2002)) with the computational domain size 960 × 960 × 500 grid cells. The model and setup are described in detail in Chandrakar *et al.*, (2022, 2023)
- temperature boundary conditions are consistent with the experiments, the Eulerian temperature time series are outputted at 0.0012–0.0015 s



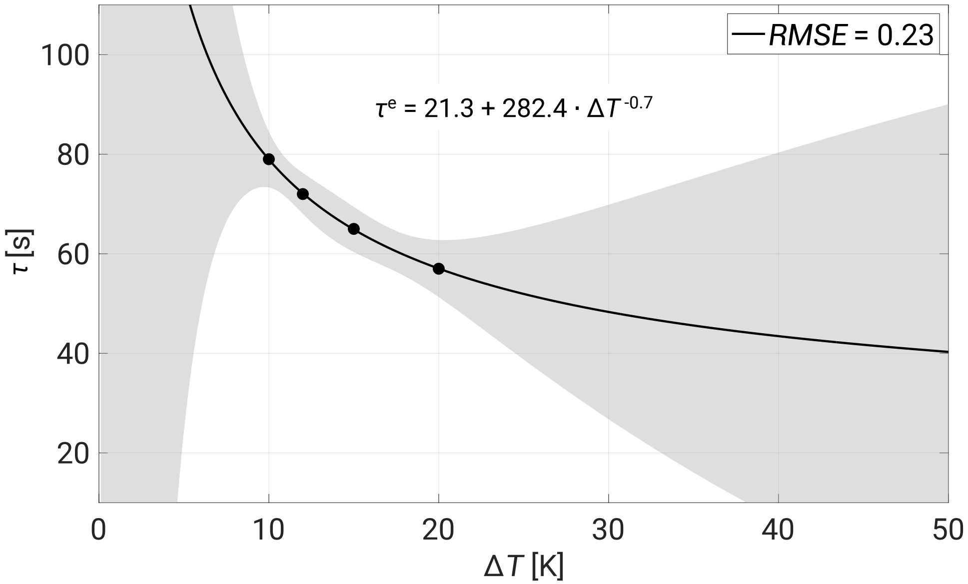
DNS vs experiment – skewness



large-scale circulation



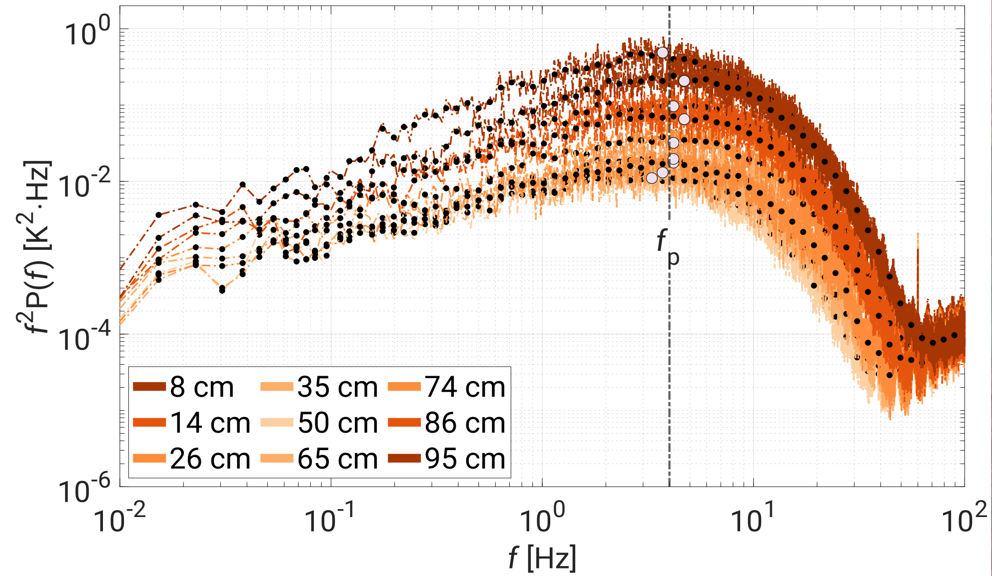
- vertical variability of the LSC period
- grey regions describe +/- 1σ
- $\tau_{12} \approx 72$ s obtained by Anderson *et al.* (2021) for $\Delta T = 12$ K

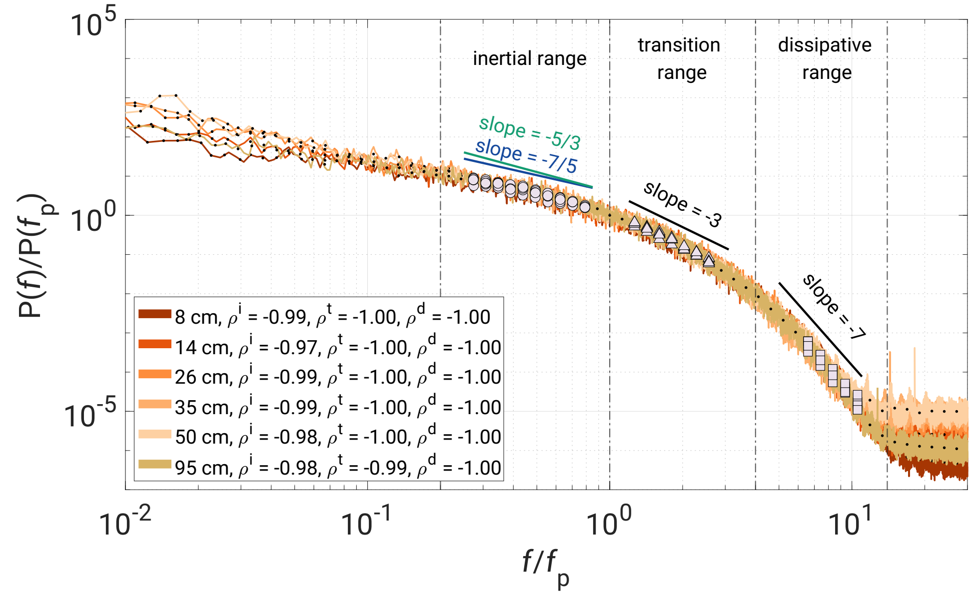


- relationship between τ and ΔT modeled by exponential function
- plot includes 95% simultaneous functional bounds, and root mean squared error (*RMSE*)

Power Spectral Density – collapse

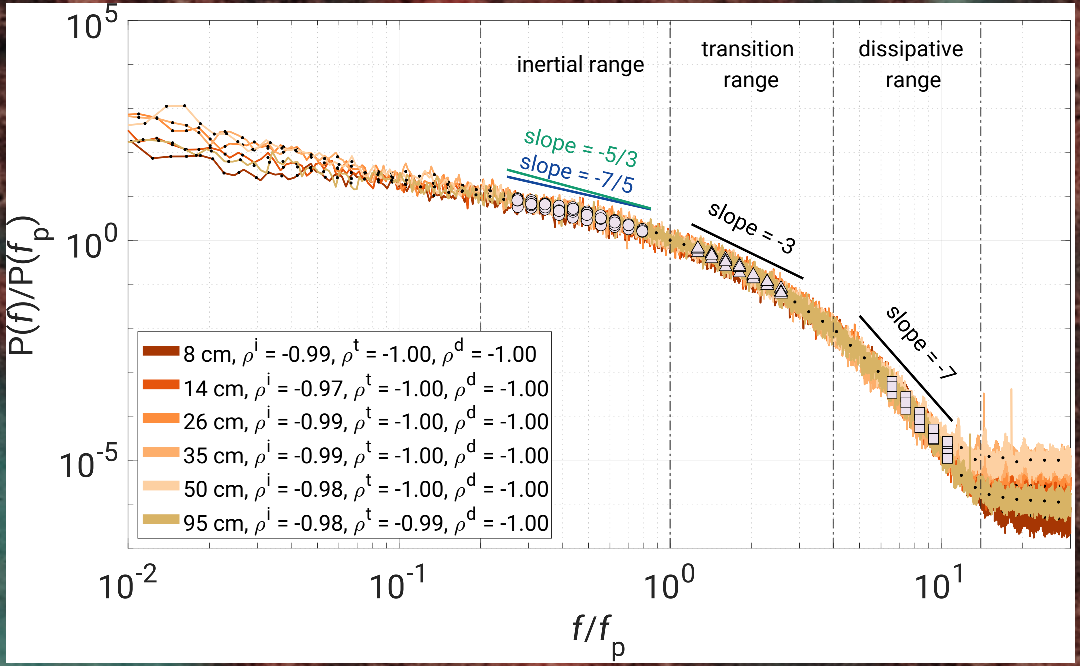
- scaling method proposed by Zhou and Xia (2001) – $f^2P(f)$ – to collapse the PSD curves
- high convergence across all curves around $f_p = 4$ Hz

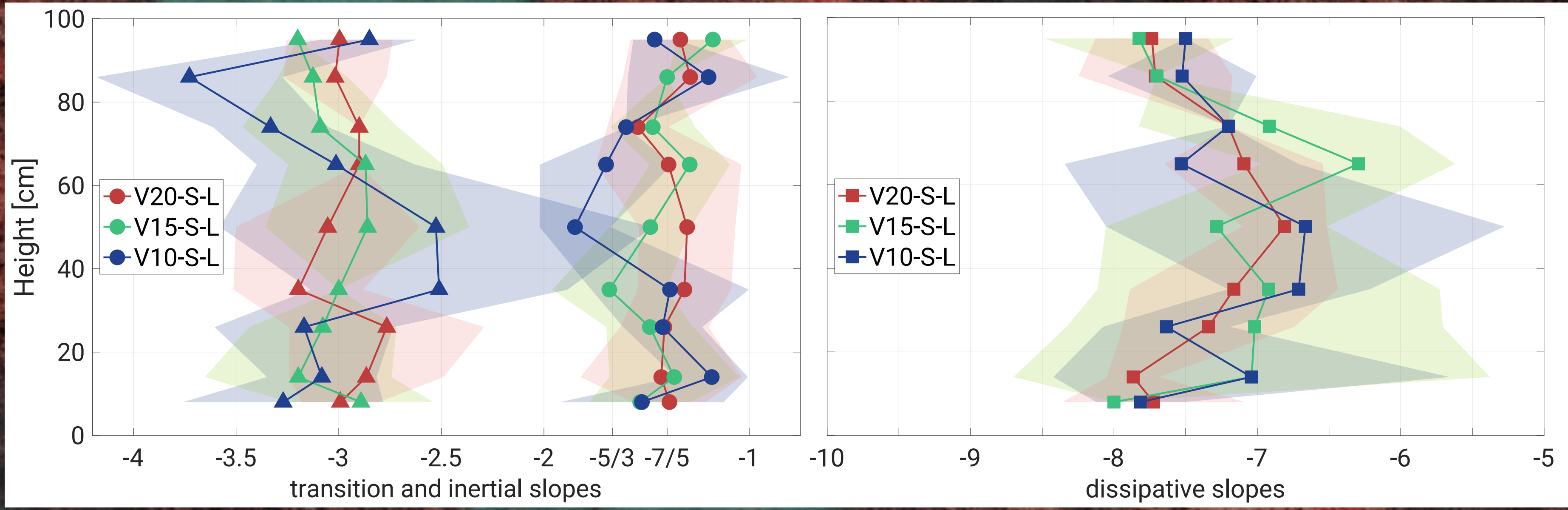




- three spectrum regimes: inertial, transition, and dissipative
- linearity of the slopes in log-log coordinates estimated with the Pearson correlation coefficient *p*

Power Spectral Density – slopes





Passive scalar spectrum

- no direct references in the literature address the subsequent regime scalings (~−3 and ~−7) or the roll-off region of the scalar spectrum
- recent investigations of the dissipation range in the energy spectrum only began exploring this regime suggesting a superposition of two exponential forms (Khurshid *et al.*, 2018; Buaria and Sreenivasan, 2020).

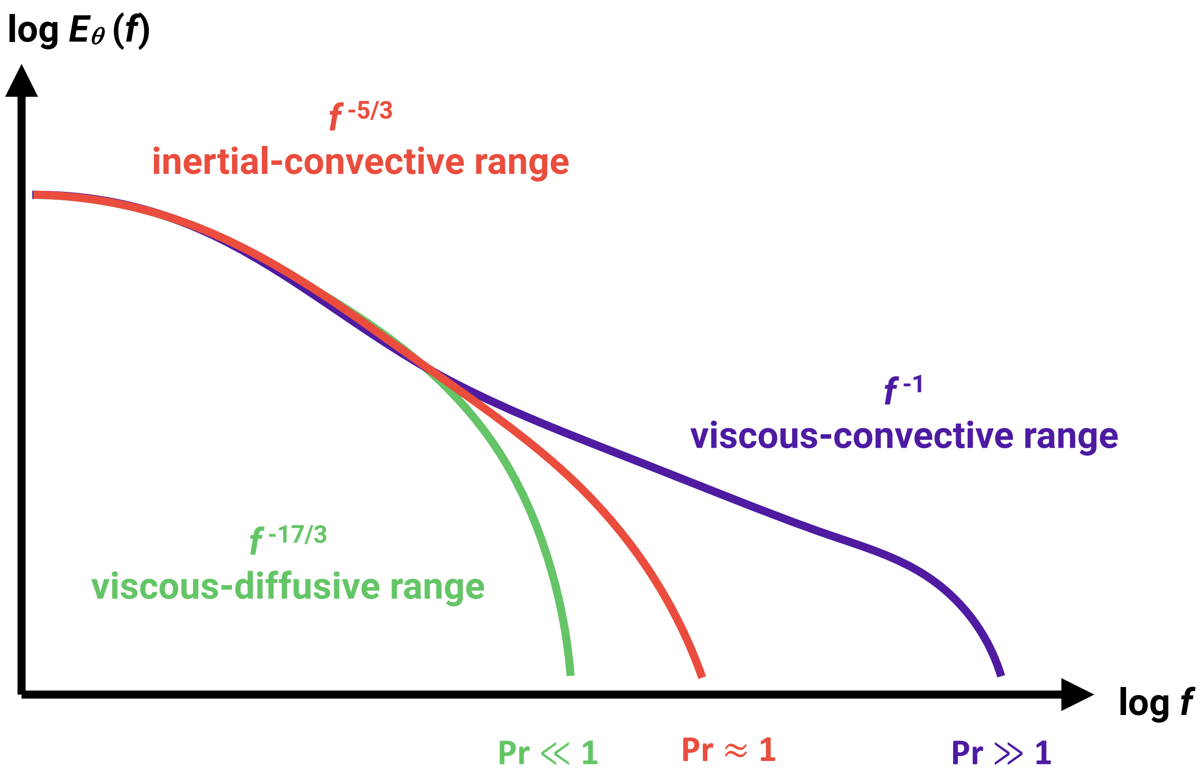
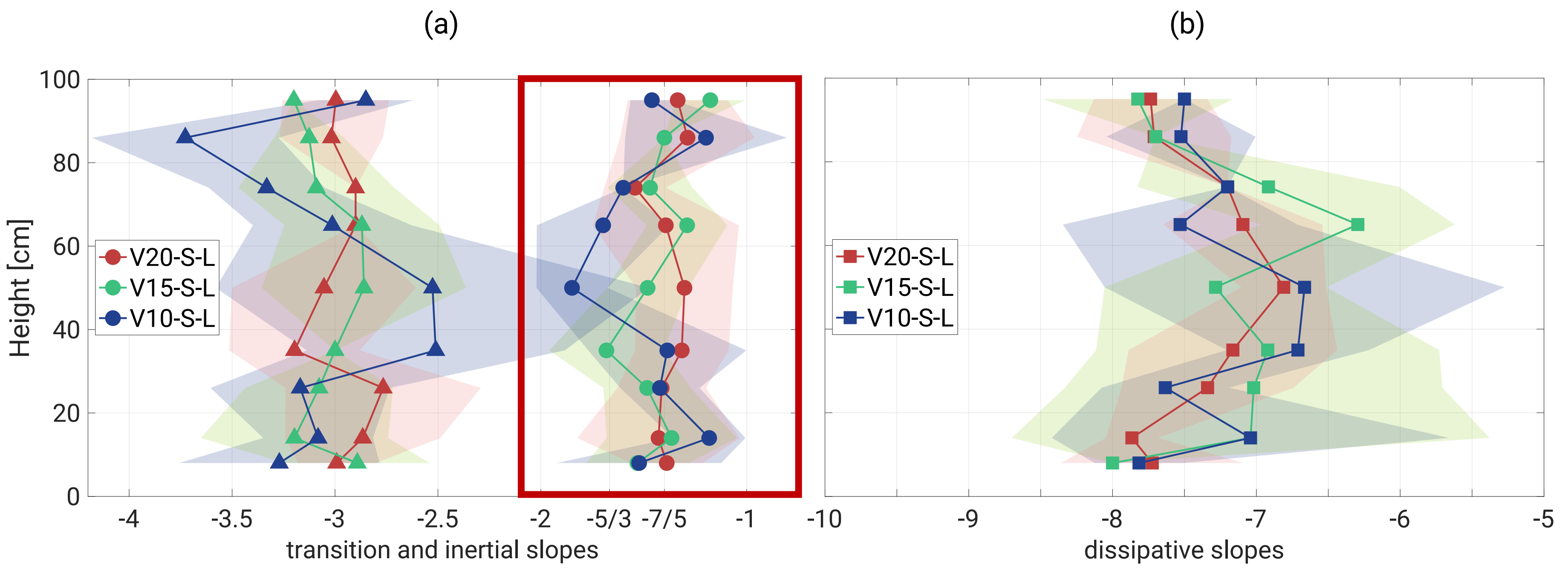


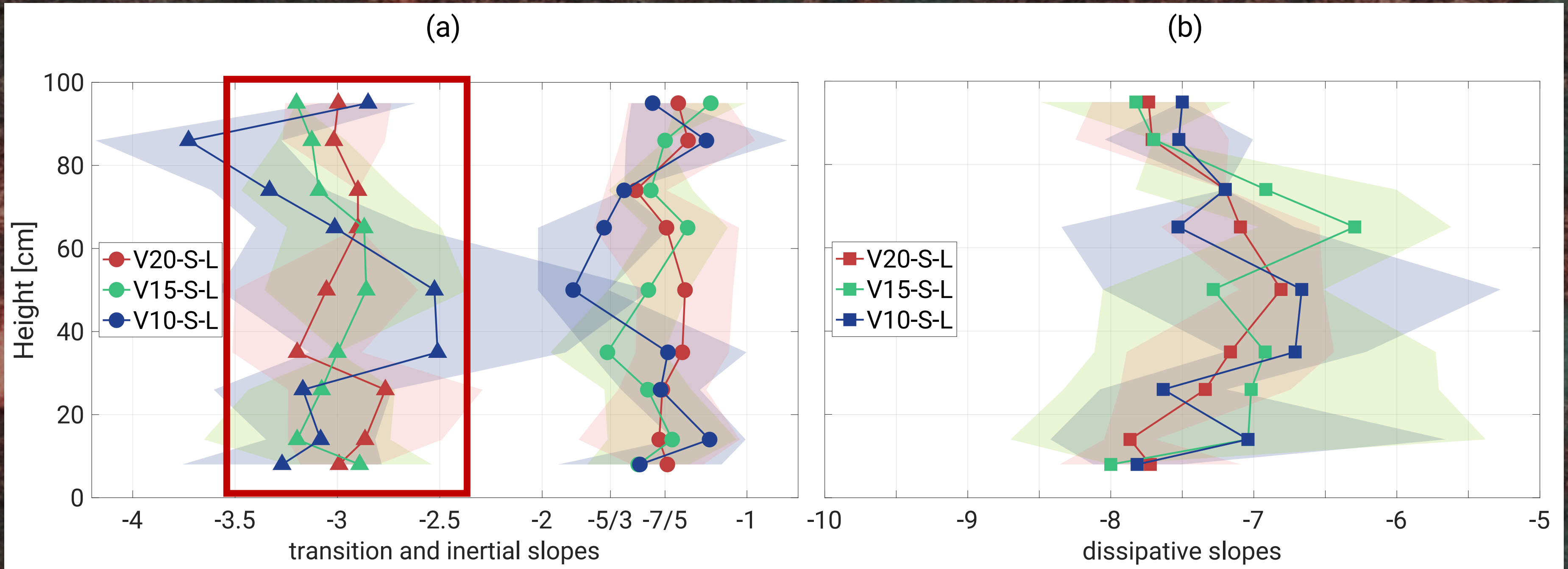
Figure adapted from Gotoh and Yeung (2012)

Power Spectral Density – slopes



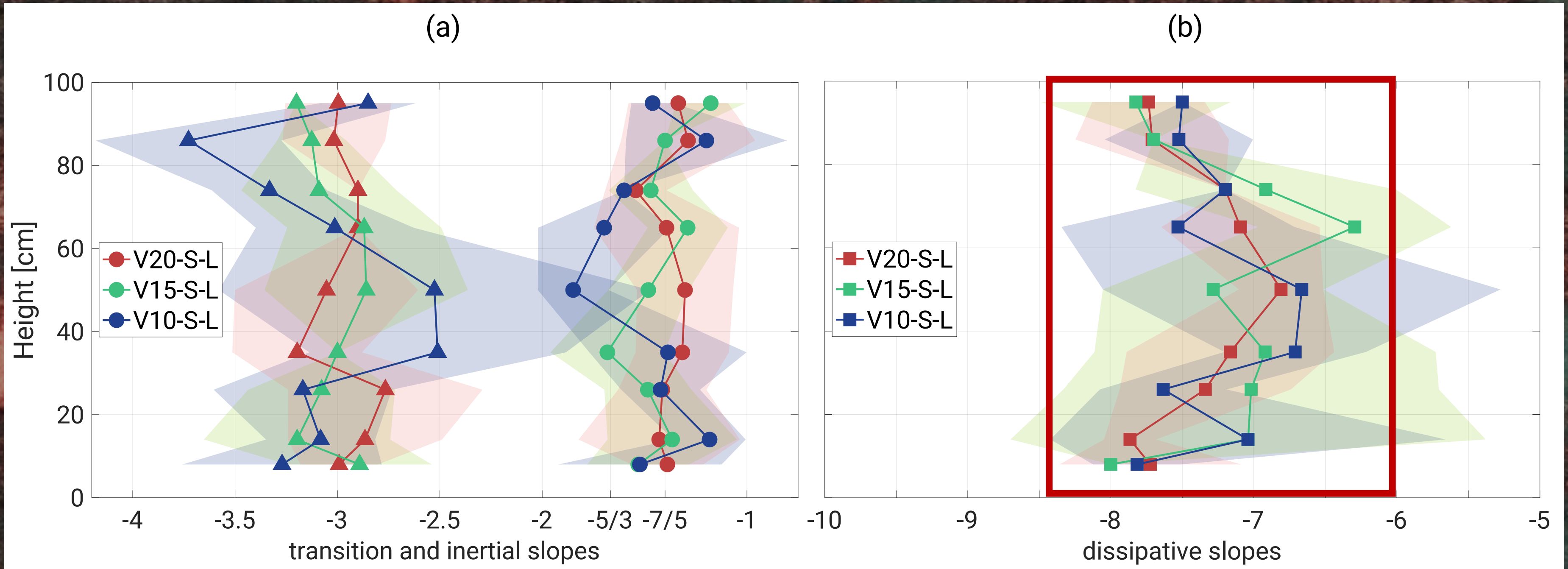
- inertial-convective regime is associated with Obukhov-Corrsin scaling (-5/3), where the temperature field does not influence the flow dynamics
- in thermally-driven convection, the flow is actively driven by temperature-induced buoyancy differences. This range is therefore redefined as the inertial-buoyancy range, where the temperature spectrum follows Bolgiano-Obukhov scaling (-7/5)

Power Spectral Density – slopes



- the −3 scaling might simply represent a crossover into the following dissipative range
- LES studies on thermal plumes (Chen and Bhaganagar, 2021, 2023, 2024):
  - ➢ density and temperature spectra scale as −2.7, strongly correlated with the velocity spectrum
  - ➢ vertical heat and mass fluxes exhibited a −3 scaling, matching the vertical component of the turbulent kinetic energy (TKE) spectrum
  - ➢ both spectra of 2D TKE, horizontal structures of 3D TKE, as well as helicity, consistently exhibited slopes of−5/3 and−3 respectively

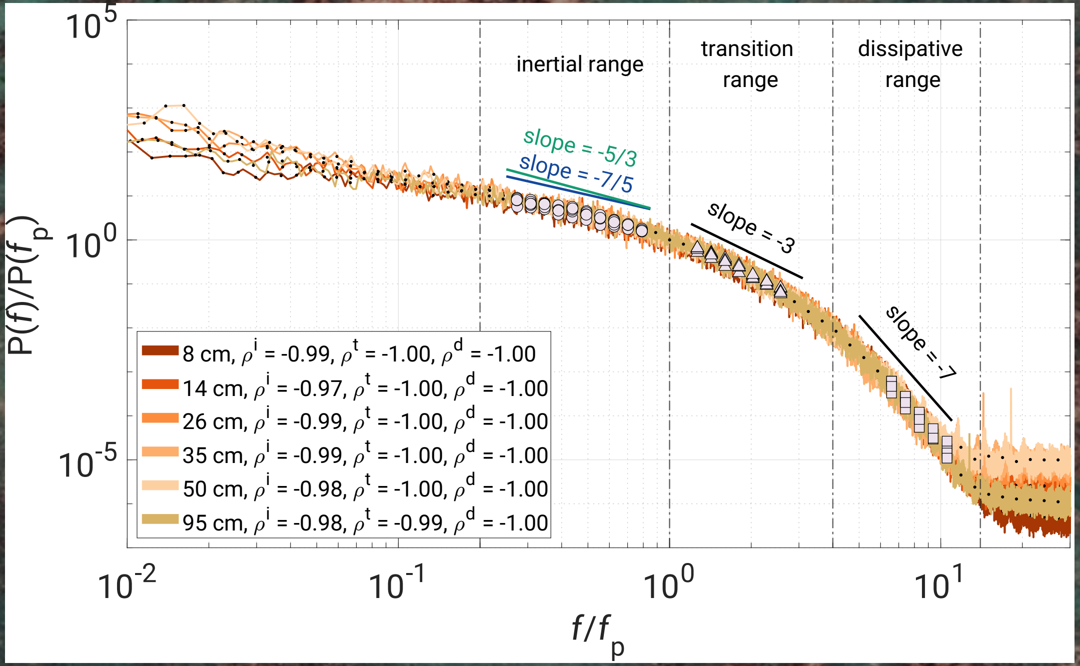
Power Spectral Density – slopes



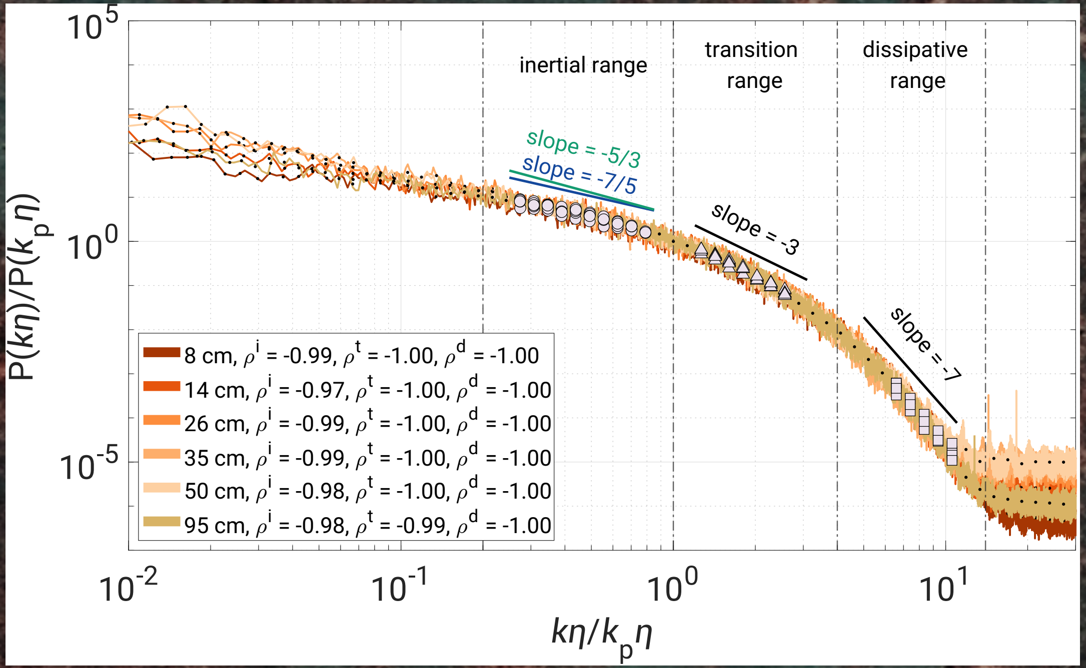
- according to Sreenivasan (2019), no scalar spectrum description exists for the dissipative regime
- in the given study a single power law seemed to be sufficient to describe this regime

Power Spectral Density in wavenumber picture

$$k \approx \tilde{f} = f(2\pi)U$$



$$P(k) \approx P(\tilde{f}) = P(f)U/2\pi$$



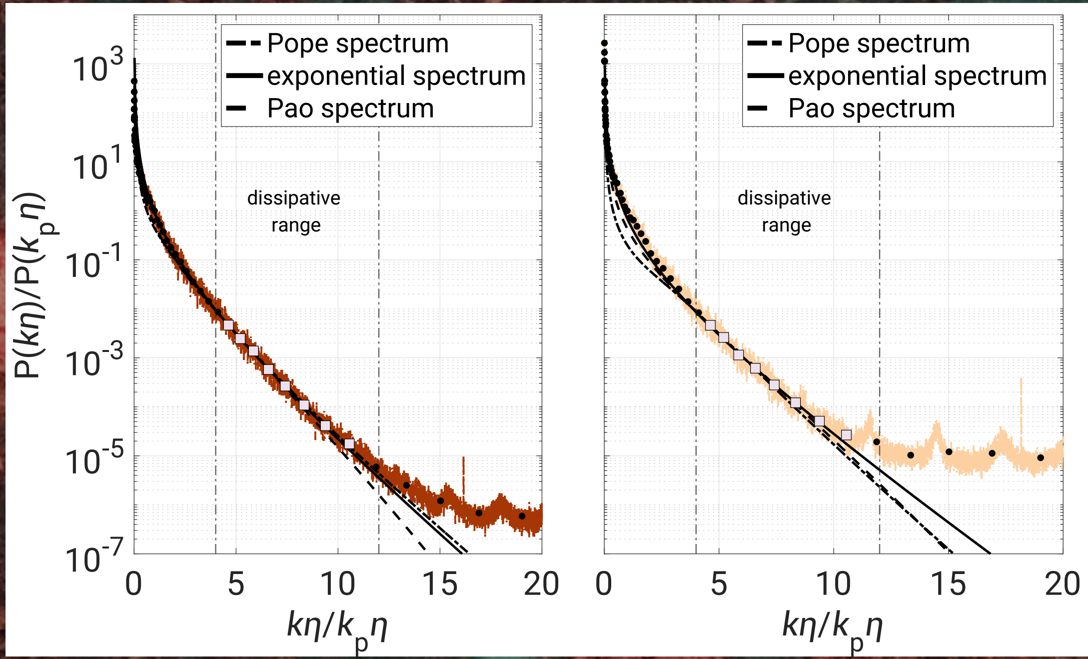
Power Spectral Density in wavenumber picture

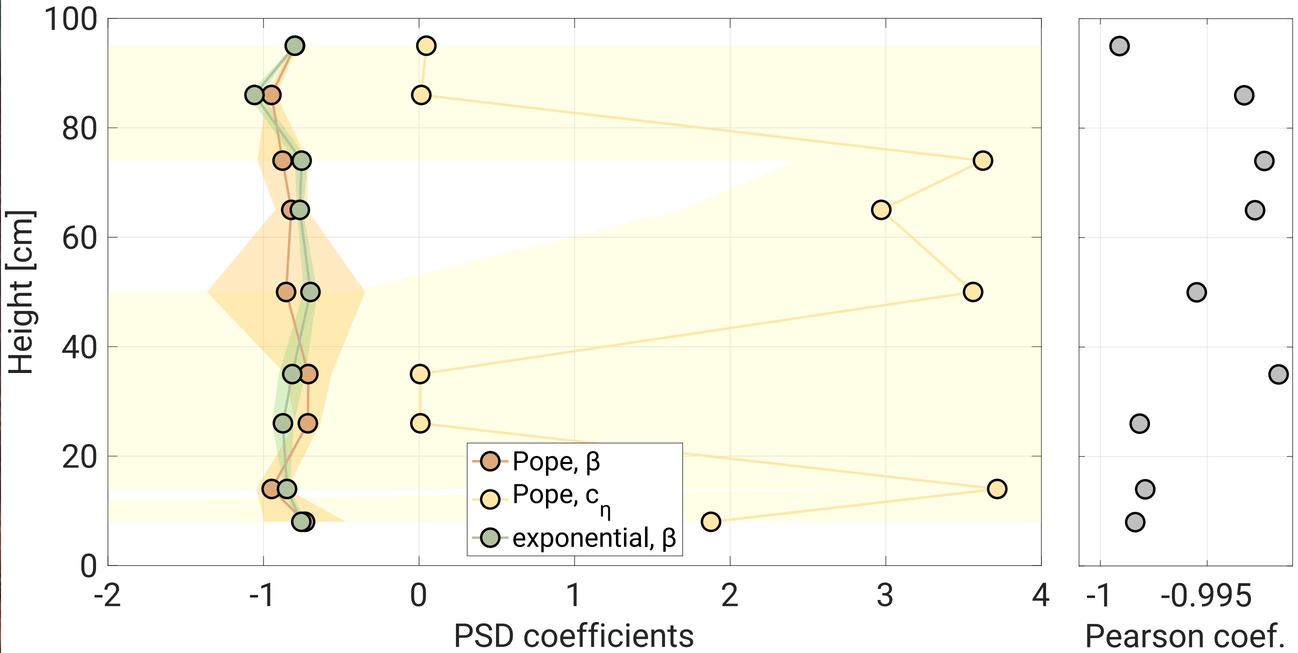
$$E(k) = C_K \langle \epsilon \rangle^{2/3} k^{-5/3} \underbrace{\boxed{f_L(kL)}}_{\approx 1} f_\eta(k\eta)$$

- Pope: $f_\eta(k\eta) = \exp\left(-\beta\left\{\left[(k\eta)^4 + c_\eta^4\right]^{1/4} - c_\eta\right\}\right)$
- exponential: $f_\eta(k\eta) = \exp(-\beta k\eta)$
- Pao: $f_\eta(k\eta) = \exp\left(-\beta\{k\eta\}^{4/3}\right)$

$$E_\theta(k) = C_O \langle \epsilon_\theta \rangle \langle \epsilon \rangle^{-1/3} k^{-5/3} f_\eta(k\eta) \quad ?$$

Power Spectral Density in wavenumber picture





$h = 8$ cm $\quad$ $h = 50$ cm

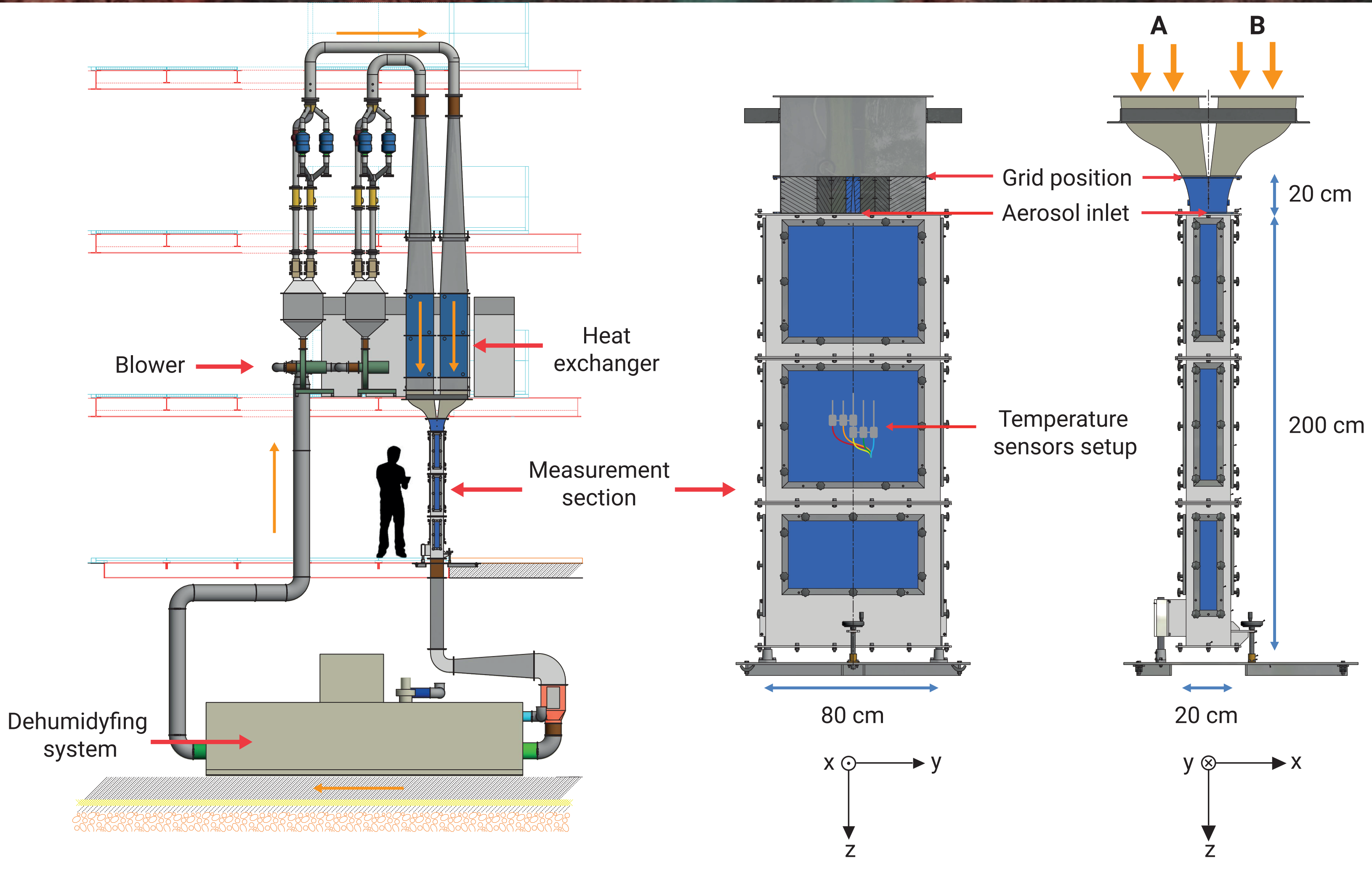
$\Delta T = 20$ K

I part-take away

- basic characteristics – significant changes in the standard deviation, skewness, and the scaling exponents of the power spectrum of the distribution of temperature fluctuations near the top and bottom surfaces -> dynamics of local thermal plumes and their interaction with the LSC
- topographic effects – no major differences were observed corresponding to topographic effects -> likely due to insufficient time series
- dynamic regimes – PSD analysis revealed periodicity of LSC with respect to the temperature differences; three distinct power-law dynamic regimes were identified: inertial ($\sim -7/5$), transition (~ -3), and dissipative (~ -7); the scale break between the inertial and transition ranges -> a dynamic transition from the LSC-dominated regime to the thermal plume regime; the following dissipative regime analyses confirmed usability of analytical approach for the scalar spectrum;
- experiment versus DNS – experimental findings showed convincing agreement with DNS conducted under similar thermodynamic conditions;
- please see Grosz R., *et al.*, (2024) for a broader discussion

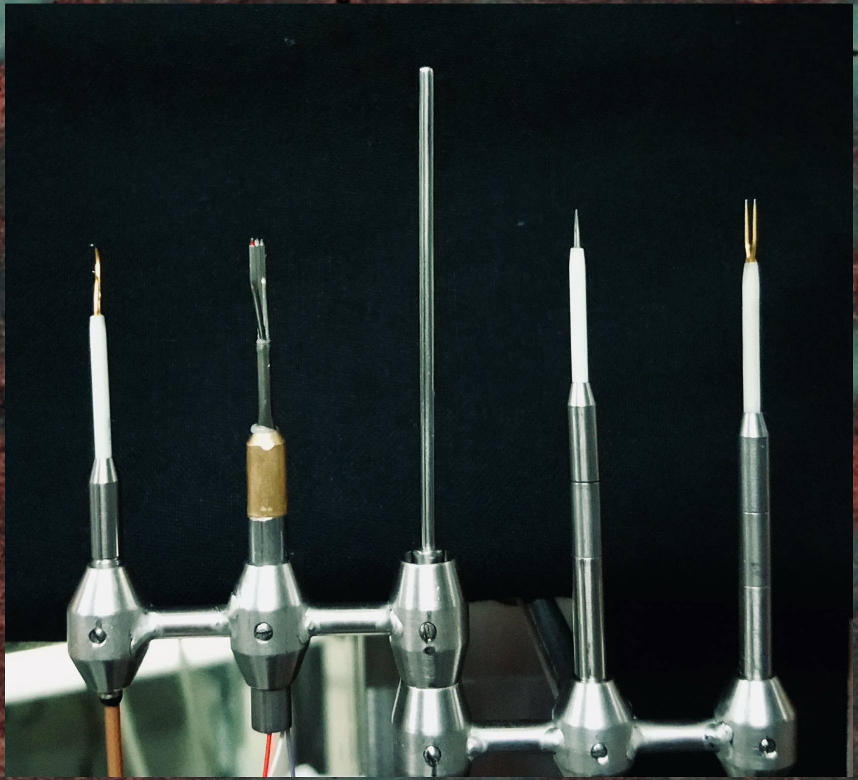
Part II
the LACIS-T wind tunnel

Setup



Niedermeier *et al.*, (2020), and Nowak *et al.*, (2022)

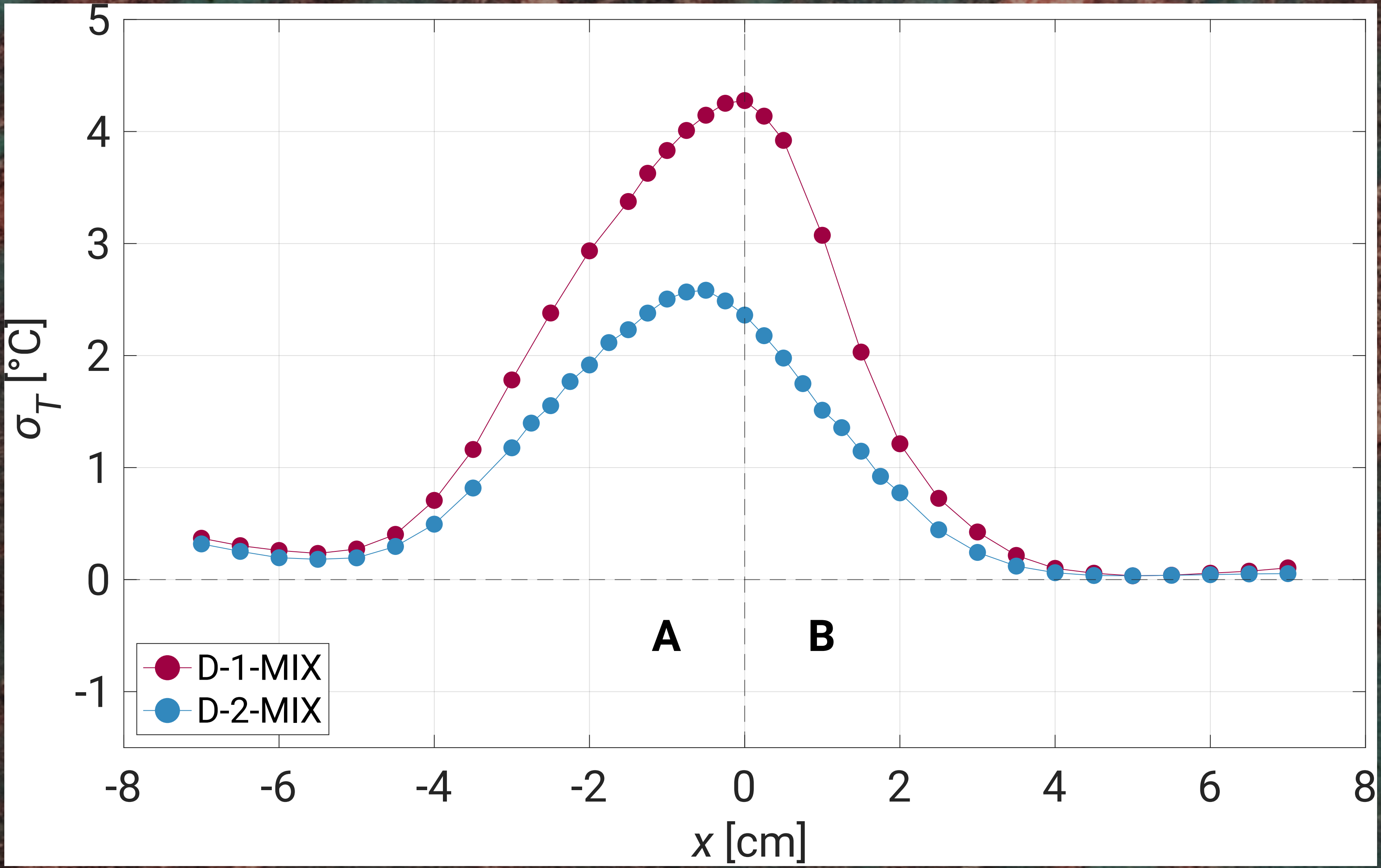
Strategy



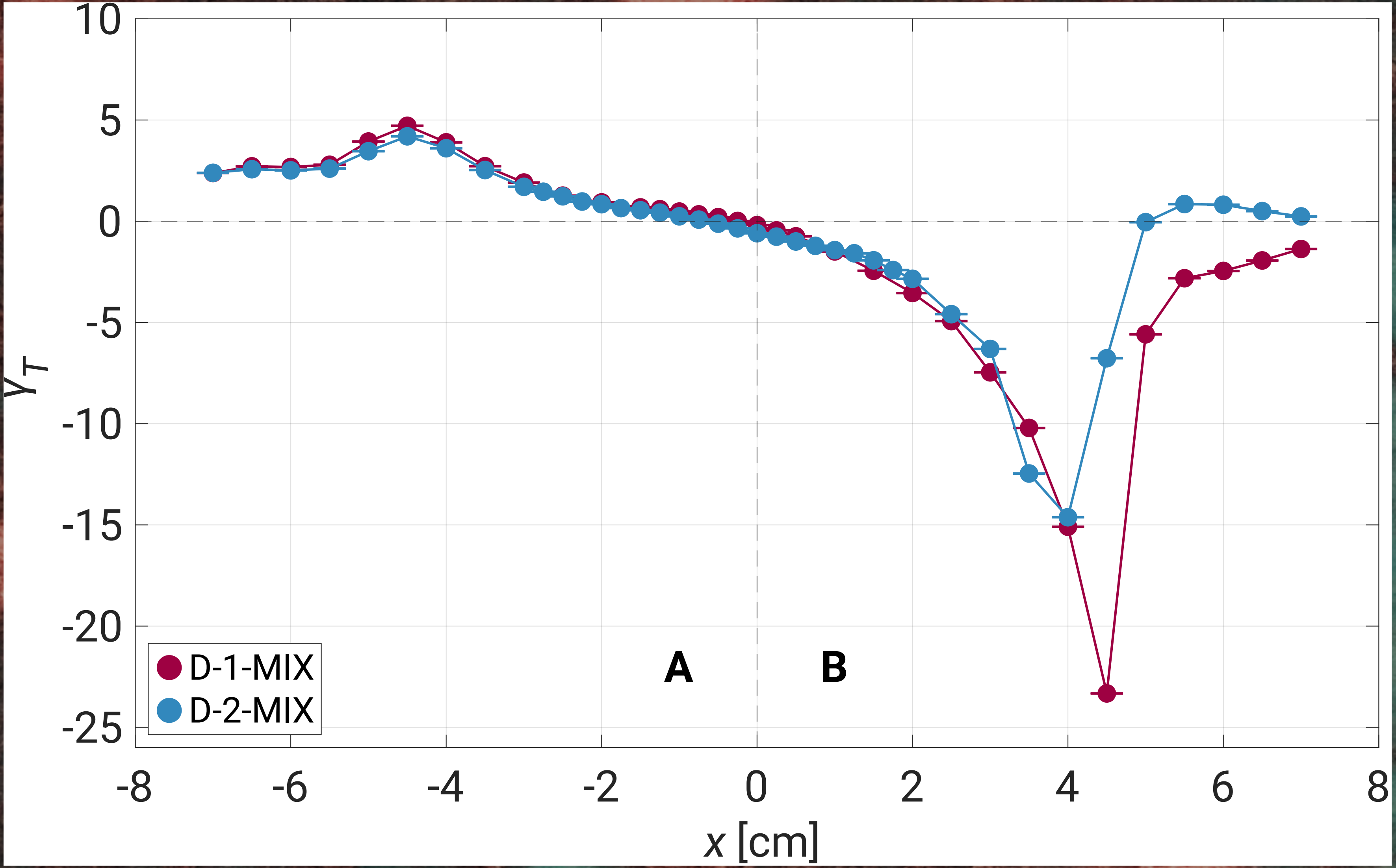
Experiment	T_A [°C]	$F_A[\mathrm{m^3\,min^{-1}}]$	T_B [°C]	$F_B[\mathrm{m^3\,min^{-1}}]$	x [cm]	t [min]
D-1-MIX	0	6.1	25	4.5	-7 to 7	10
D-2-MIX	4	4.5	20	4.5	-7 to 7	5

- high resolution (1.5 kHz) temperature time series along the *x* axis
- study performer under two ΔT: 25 K, and 16 K
- variable measurement time (10 min or 5 min)
- note different flow rates between both streams in D-1-MIX

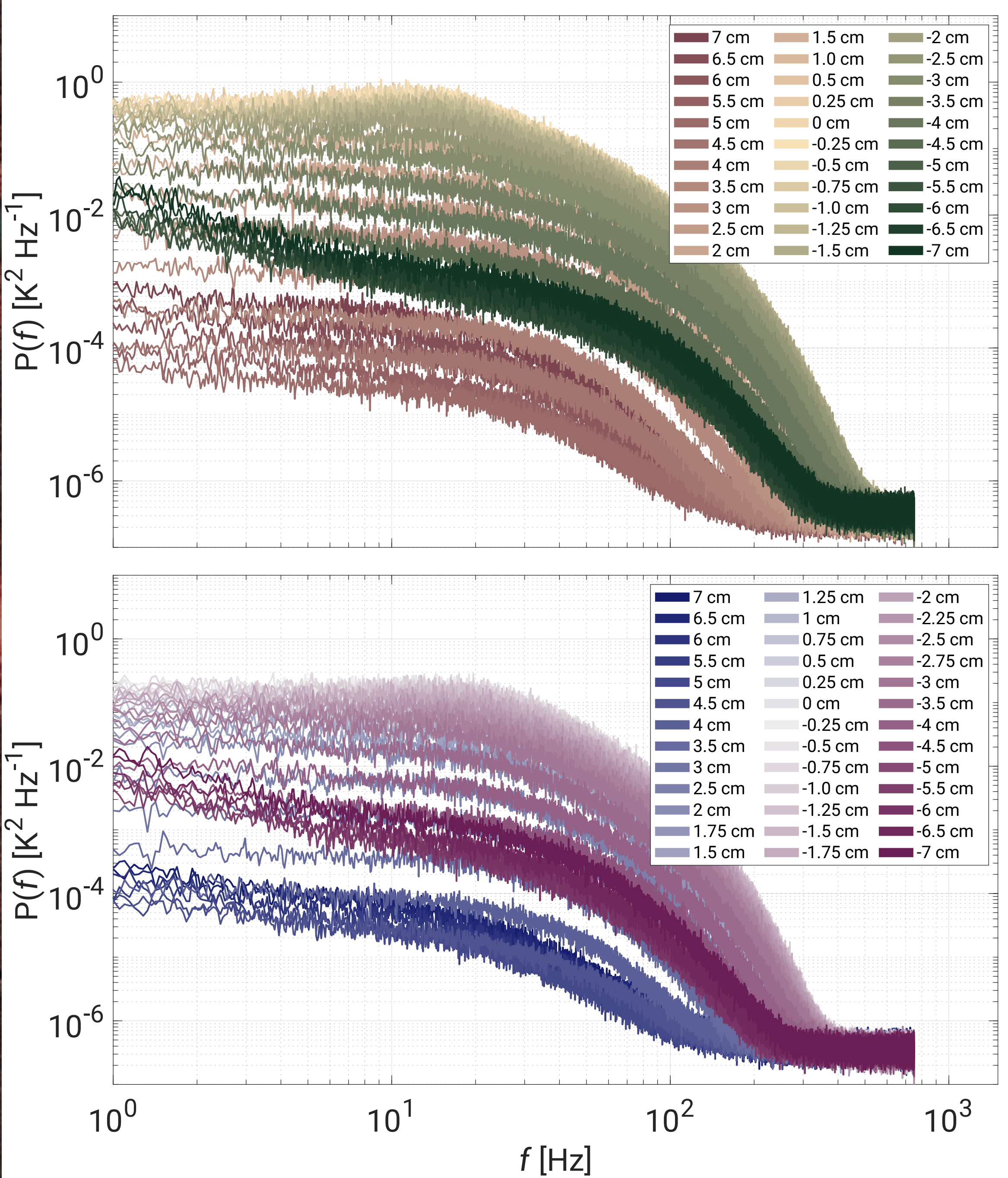
Standard deviation



Skewness



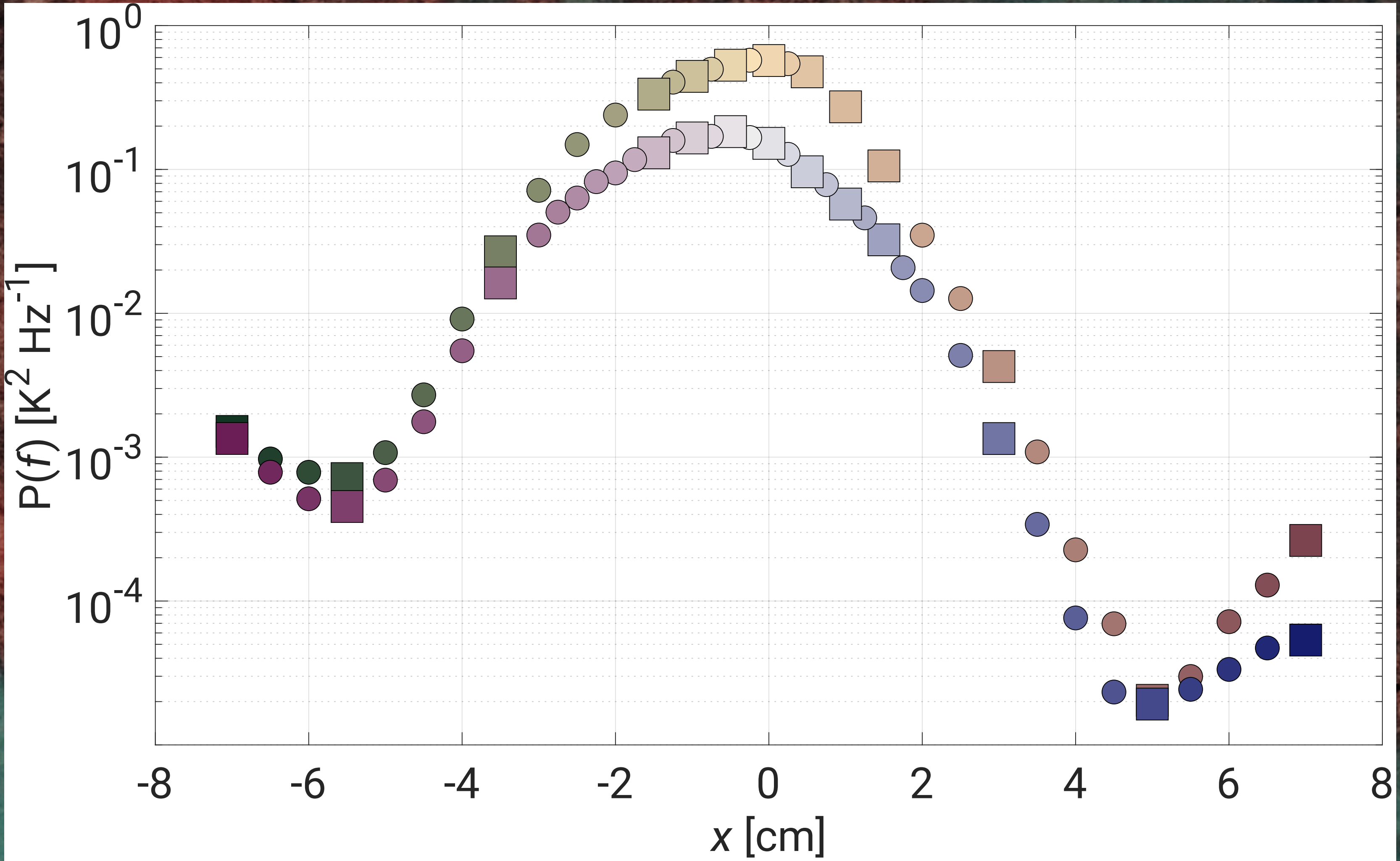
Power Spectral Density – raw



D-1-MIX

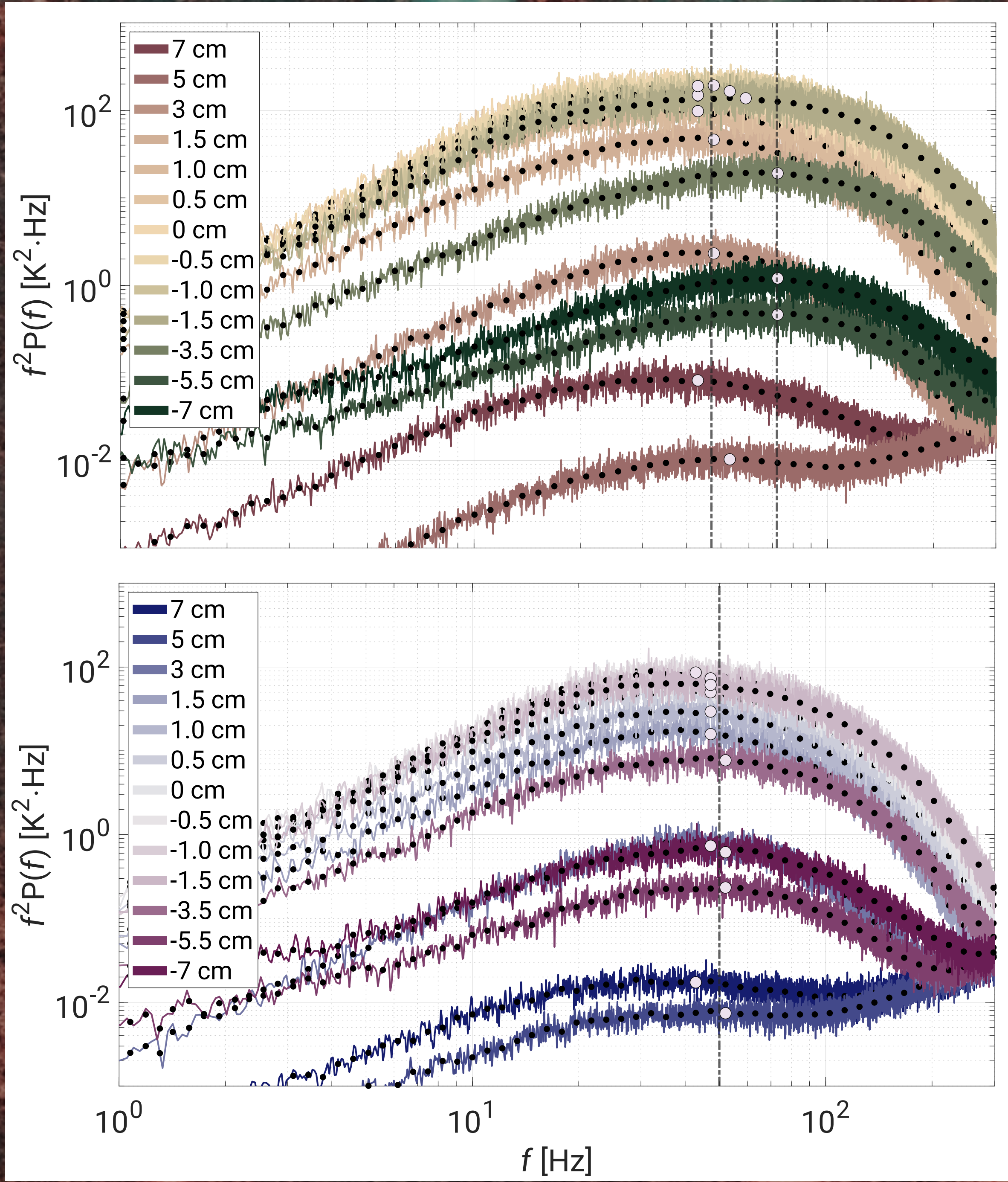
D-2-MIX

Power Spectral Density – cross-section



Power Spectral Density – collapse

- scaling method proposed by Zhou and Xia (2001) – $f^2P(f)$ – to collapse the PSD curves



D-1-MIX

- $f_p = 47$ Hz
- $f_p = 72$ Hz

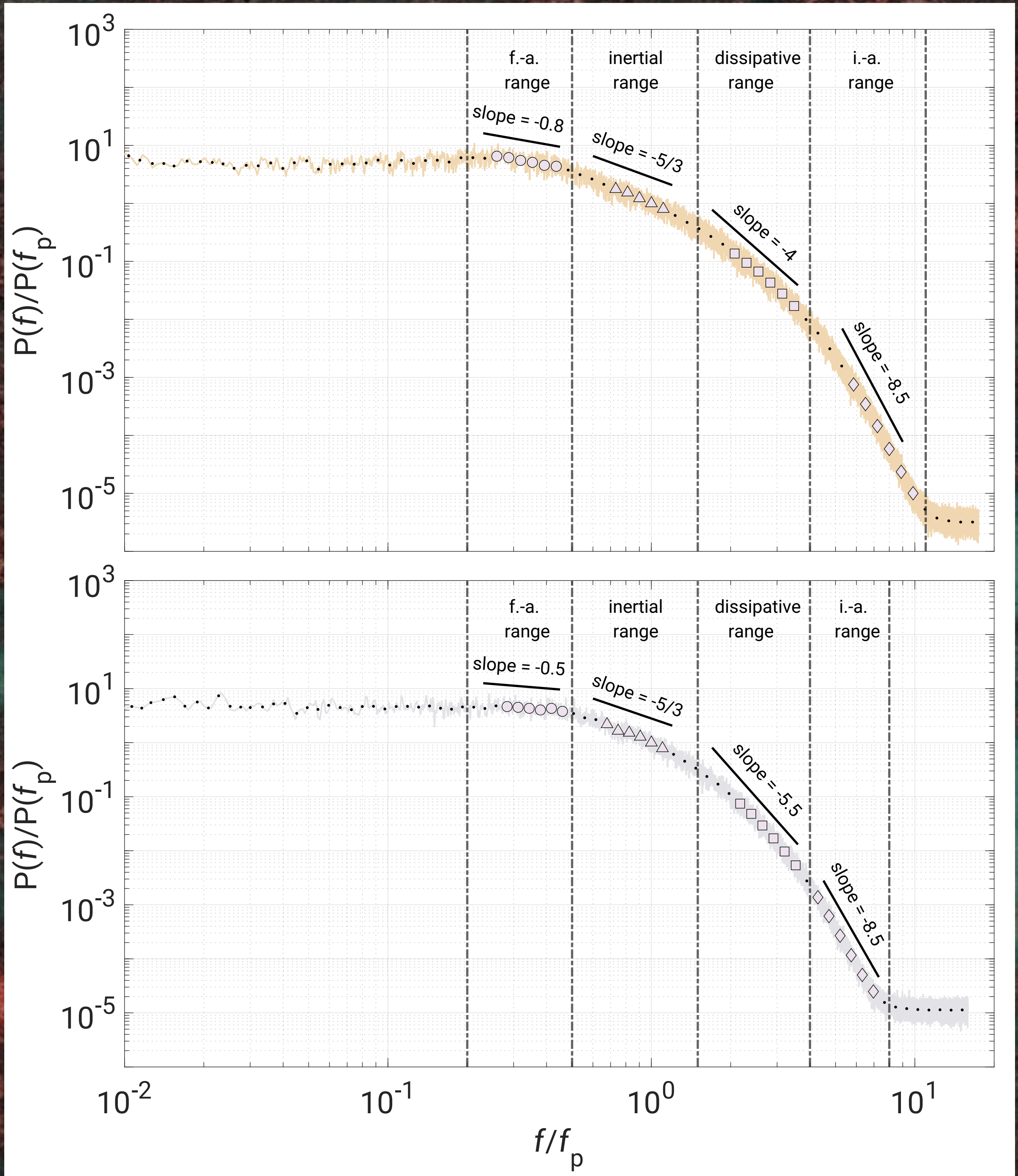
D-2-MIX

- $f_p = 50$ Hz

Power Spectral Density – regimes

Four defined regimes:

- facility-affected range
- inertial range
- dissipative range
- instrument-affected range

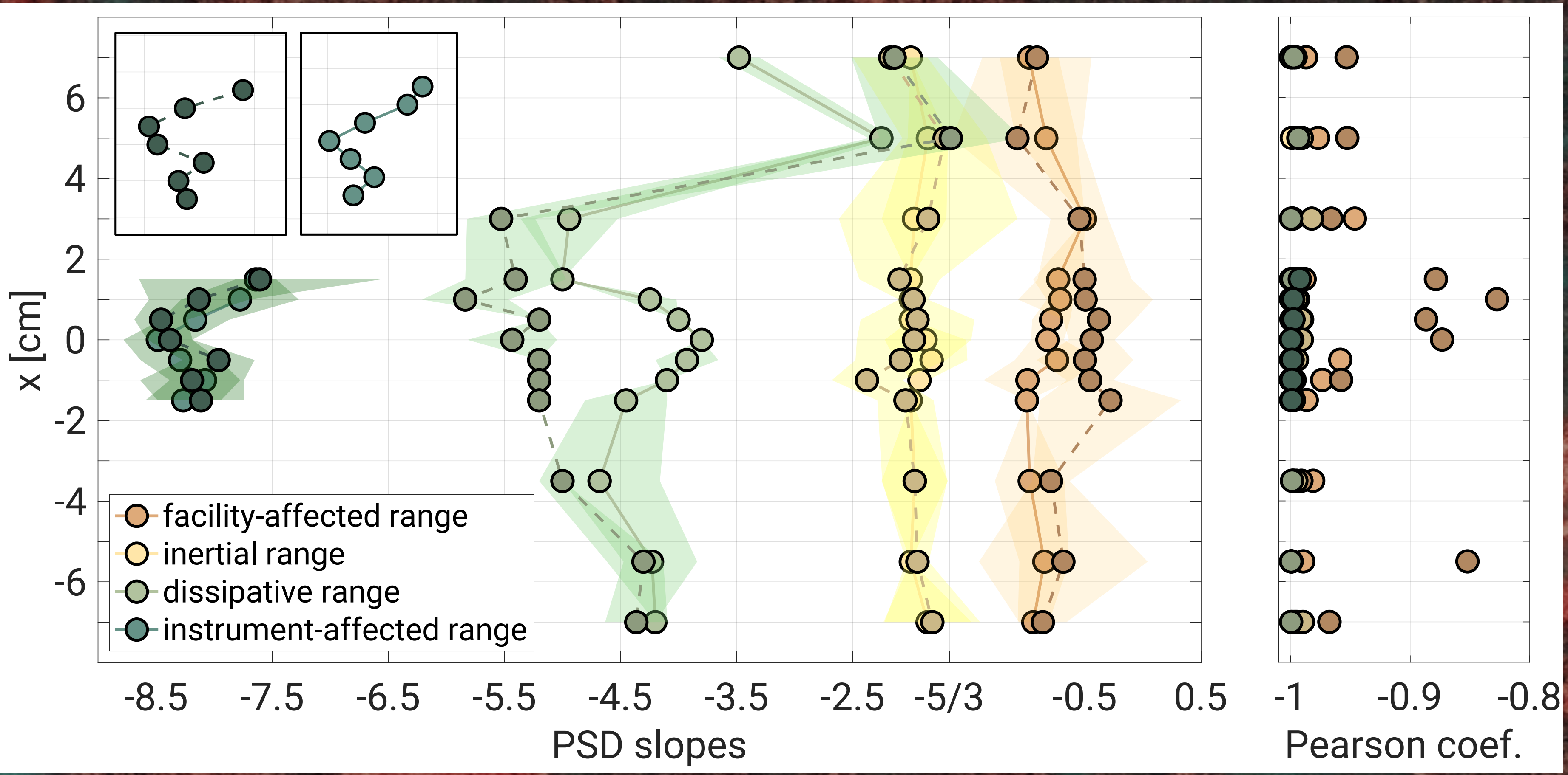


D-1-MIX

$x = 0$ cm

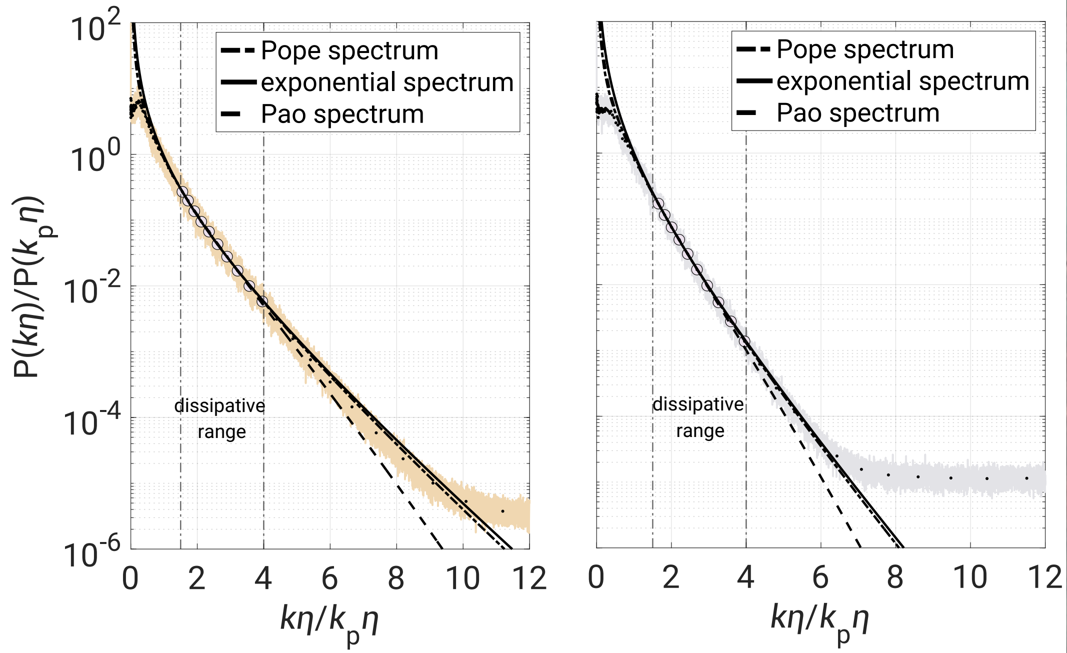
D-2-MIX

Power Spectral Density – slopes



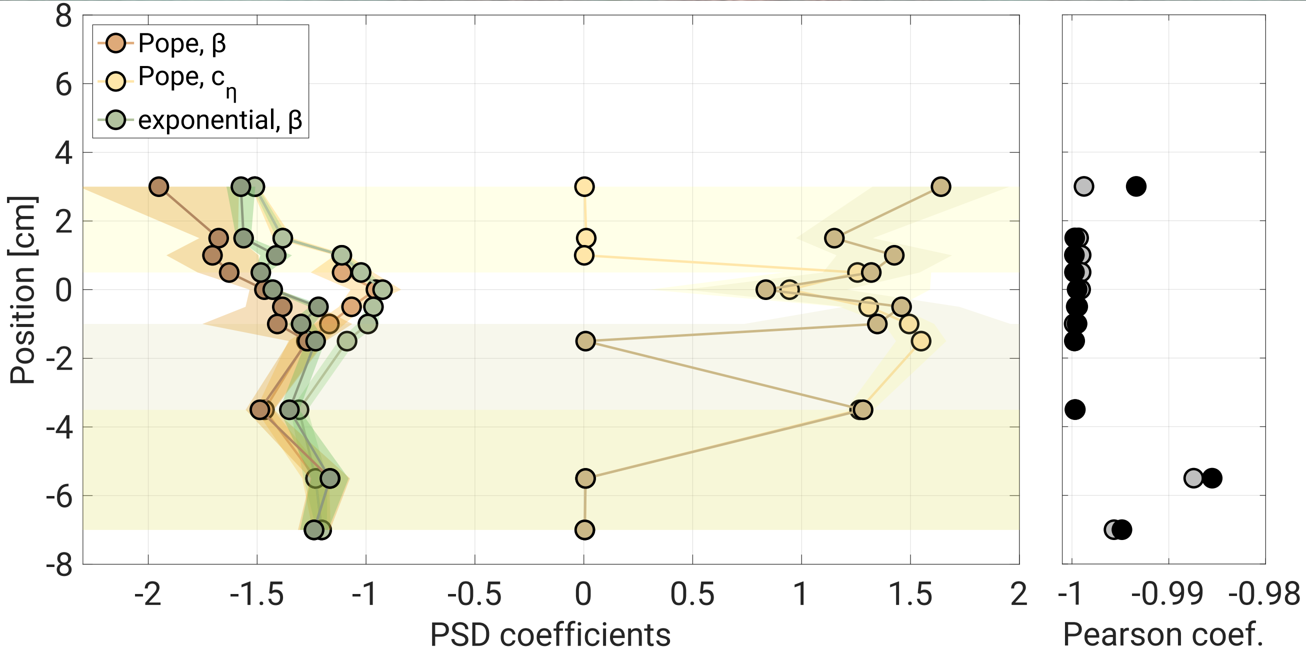
lighter color shades – D-1-MIX
darker color shades – D-2-MIX

Power Spectral Density in wavenumber picture



D-1-MIX

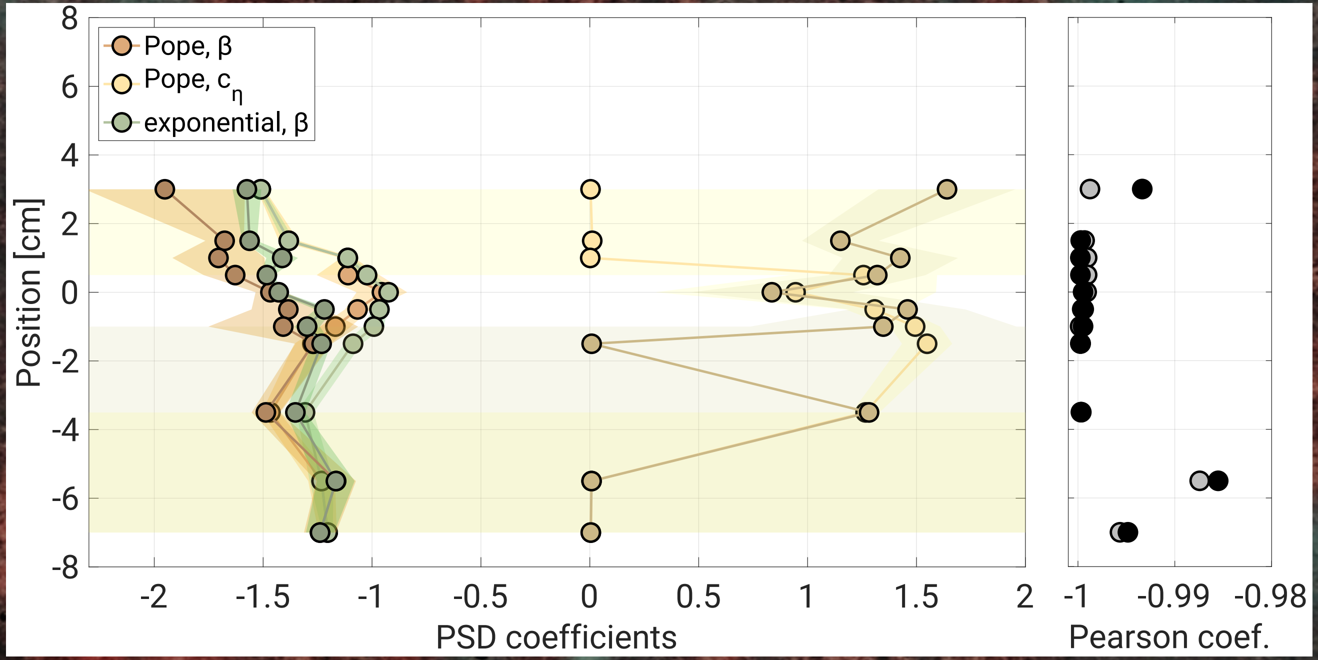
D-2-MIX



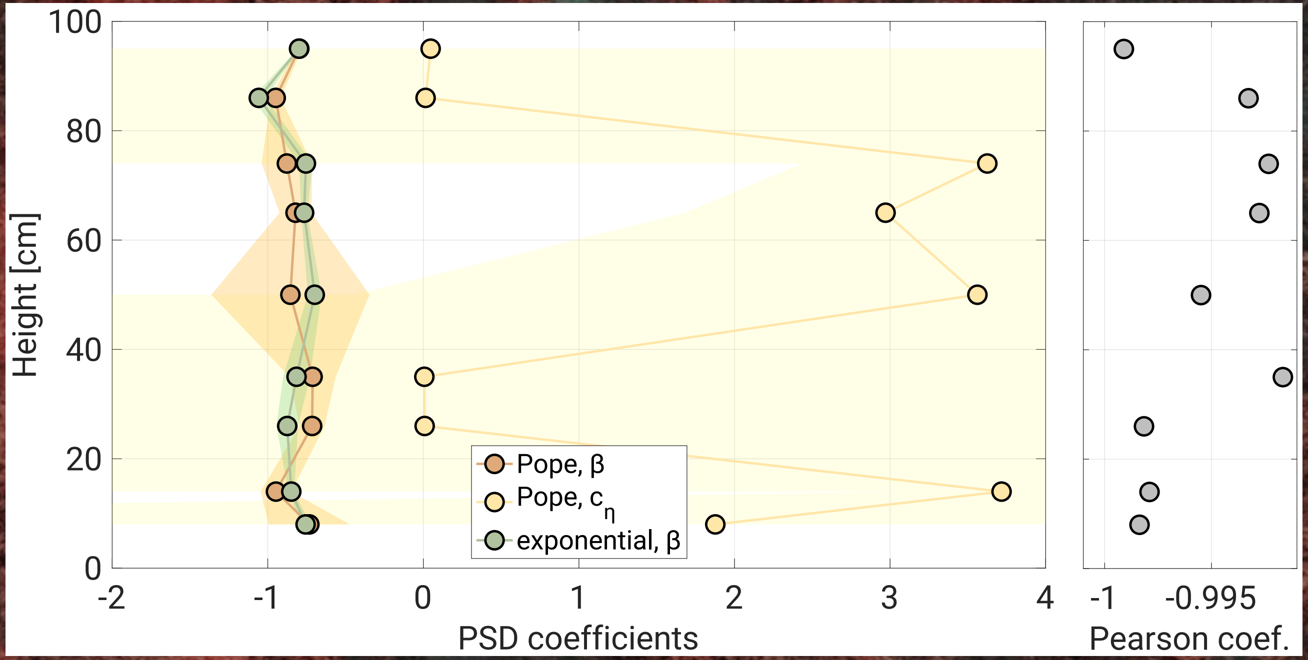
$x = 0$ cm

lighter color shades – D-1-MIX
darker color shades – D-2-MIX

Power Spectral Density – slopes



LACIS-T



Pi Chamber

II part–take away

- basic characteristics – standard deviation peaks shift atributted to differences in mixing dynamics between both cases; strong skewness inhomogenity present on the right side of the tunnel -> likely due to obstacle presence; outside conditions affect regions near the windows;

- dynamic regimes – PSD analysis showed changing intensity of power spectra across the tunnel; four distinct power-law dynamic regimes were identified: facility-affected (~−0.5 or ~−0.8), inertial (~−5/3), dissipative (~−4 or ~−5.5), and instrument-affected (~−8.5); the following dissipative regime analyses confirmed usability of analytical approach for the scalar spectrum showing that in the smallest scales LACIS-T results are consistent with the previous findings from the Pi Chamber;