Small-scale turbulence in trade-wind atmospheric boundary layer in EUREC4A observations

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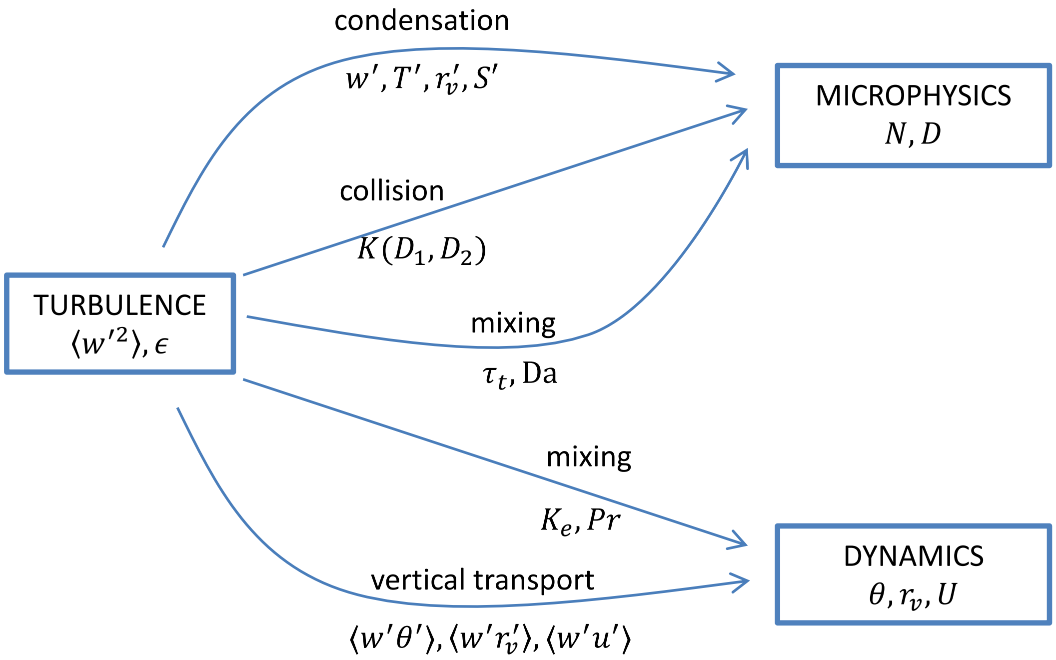
UNIVERSITY OF WARSAW | INSTITUTE OF GEOPHYSICS

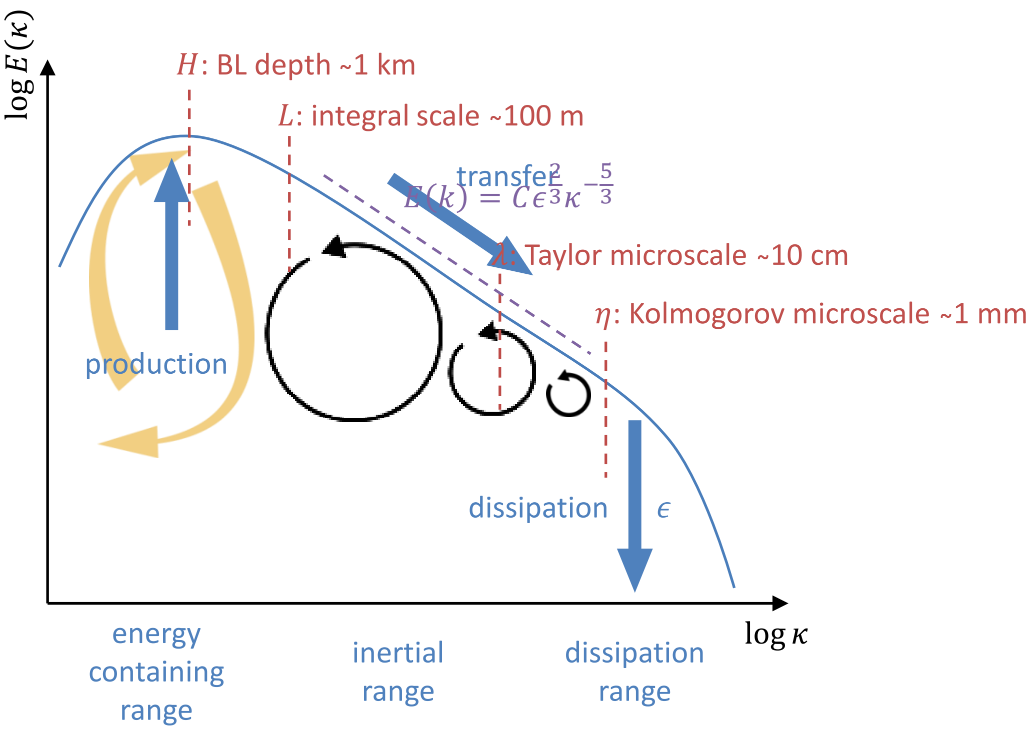
EUREC4A meeting

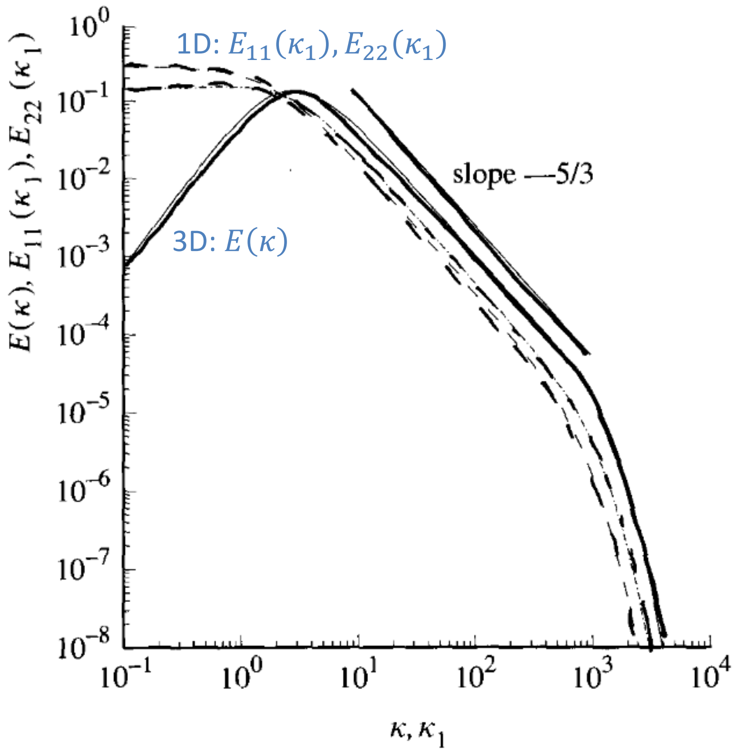
6.04.2023

Importance of turbulence



Turbulence eddy cascade





modeled spectrum

Pope 2000

Inertial range scaling

Homogeneous isotropic turbulence under Kolmogorov hypotheses

3D velocity spectrum

$$E(k) = C\epsilon^{\frac{2}{3}}\kappa^{-\frac{5}{3}}$$

1D velocity spectra

Longitudinal $E_L(\kappa_L) = C_L\epsilon^{\frac{2}{3}}\kappa_L^{-\frac{5}{3}}$ u

Transverse $E_T(\kappa_L) = C_T\epsilon^{\frac{2}{3}}\kappa_L^{-\frac{5}{3}}$ v, w

2nd order velocity structure functions

e.g. $D_u(r) = \langle[u(x+r) - u(x)]^2\rangle$

Longitudinal $D_L(r) = B_L\epsilon^{\frac{2}{3}}r^{\frac{2}{3}}$ u

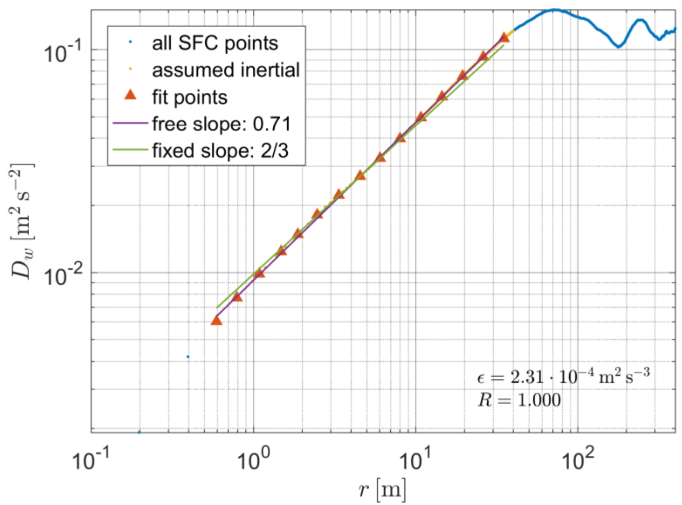
Transverse $D_T(r) = B_T\epsilon^{\frac{2}{3}}r^{\frac{2}{3}}$ v, w

Universal constants

$C \approx 1.5 \quad C_L \approx 0.49 \quad C_T \approx 0.65 \quad B_L \approx 2.0 \quad B_T \approx 2.6$

Practical estimation of TKE dissipation rate

Nowak et al. 2021



Dissipation fit $D_w(r) = B_T(\epsilon_w r)^{\frac{2}{3}}$

Scaling fit $D_w(r) = B^* r^{s_w}$

Correlation $R_w(\log r, \log D_w)$

+ analogously for u, v or spectrum scaling …

Anisotropy of atmospheric turbulence

Isotropic turbulence

$$\langle u'^2 \rangle = \langle v'^2 \rangle = \langle w'^2 \rangle$$
$$\epsilon_u = \epsilon_v = \epsilon_w$$

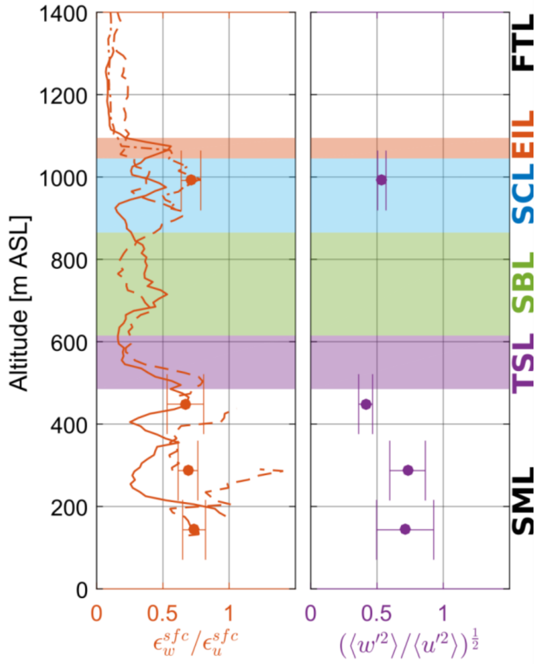
Anisotropic turbulence

$$A_{var} = \frac{2\langle w'^2 \rangle}{\langle u'^2 \rangle + \langle v'^2 \rangle} \neq 1$$

$$A_\epsilon = \sqrt{\frac{2\epsilon_w^2}{\epsilon_u^2 + \epsilon_w^2}} \neq 1$$

Anisotropy in a decoupled stratocumulus-topped marine boundary layer

Nowak et al. 2021



Turbulence kinetic energy budget

$$\frac{\partial}{\partial t} TKE = B + S + T - \epsilon$$

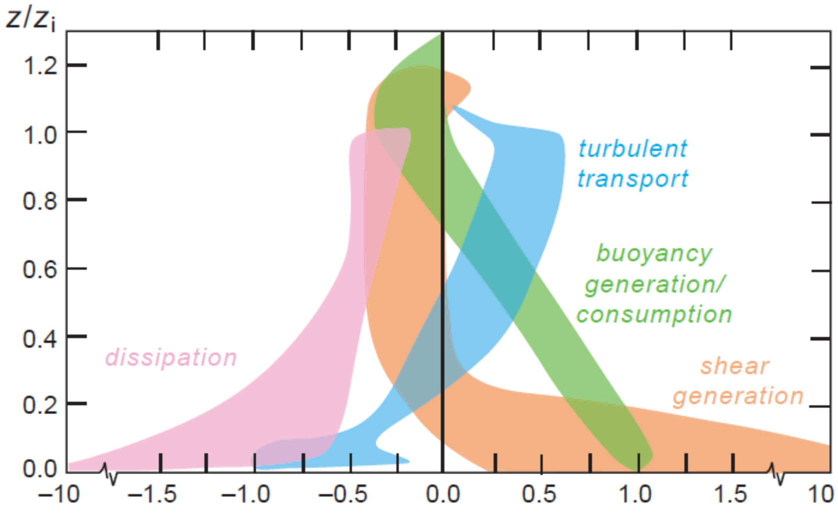
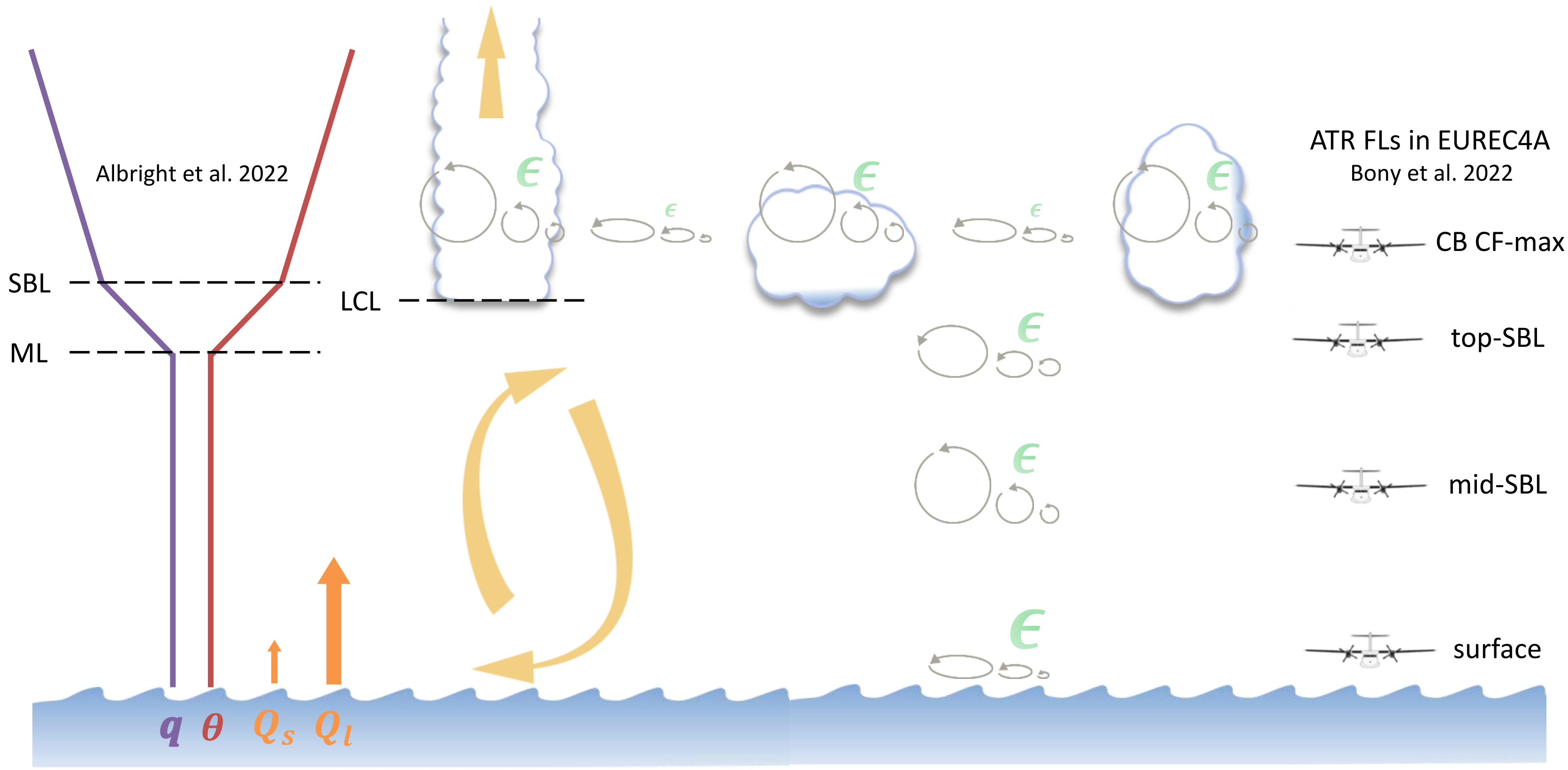


Figure 4.5 Typical ranges of terms in the TKE budget equation (4.41) during daytime, composited from observations and numerical simulations from a number of investigators. Values have been normalized by w_*^3/z_i, where z_i is the height of the inversion at the top of the boundary layer and w_* is the convective velocity scale defined as $w_* = [(g/\overline{\theta})\overline{w'\theta'}|_0\ z_i]^{1/3}$ (typically, $w_*^3/z_i \sim 6 \times 10^{-3}$ m^2 s^{-3}). (Adapted from Stull [1988].)

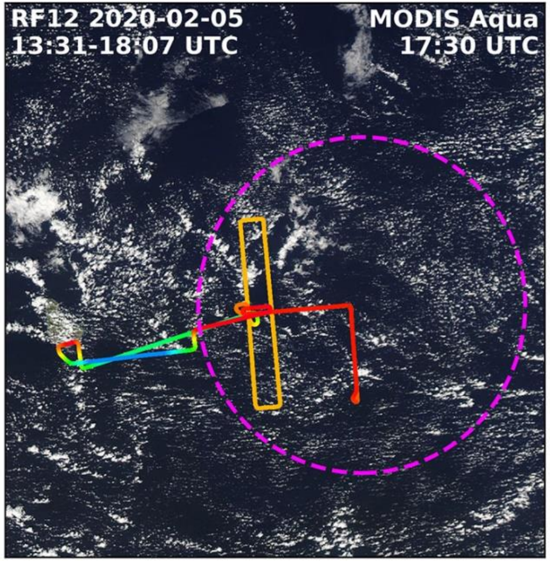
Markowski and Richardson 2010

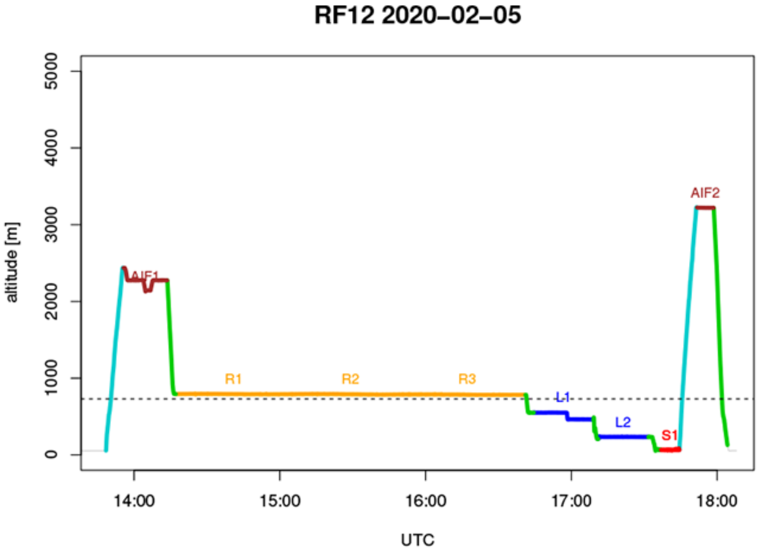
Turbulence in trade-wind atmospheric boundary layer



EUREC4A ATR-32 flight patterns

Rectangles 120x20 km perpendicular to the mean easterly wind at **cloud base** (targeted max CF)
L-shape legs 60+60 km, along/across wind, near the **top of the SBL**, 150-200 m below cloud base
L-shape legs 60+60 km, along/cross wind, near the **middle of the SBL**
Surface leg about 40 km at 60 m





Bony et al. 2022

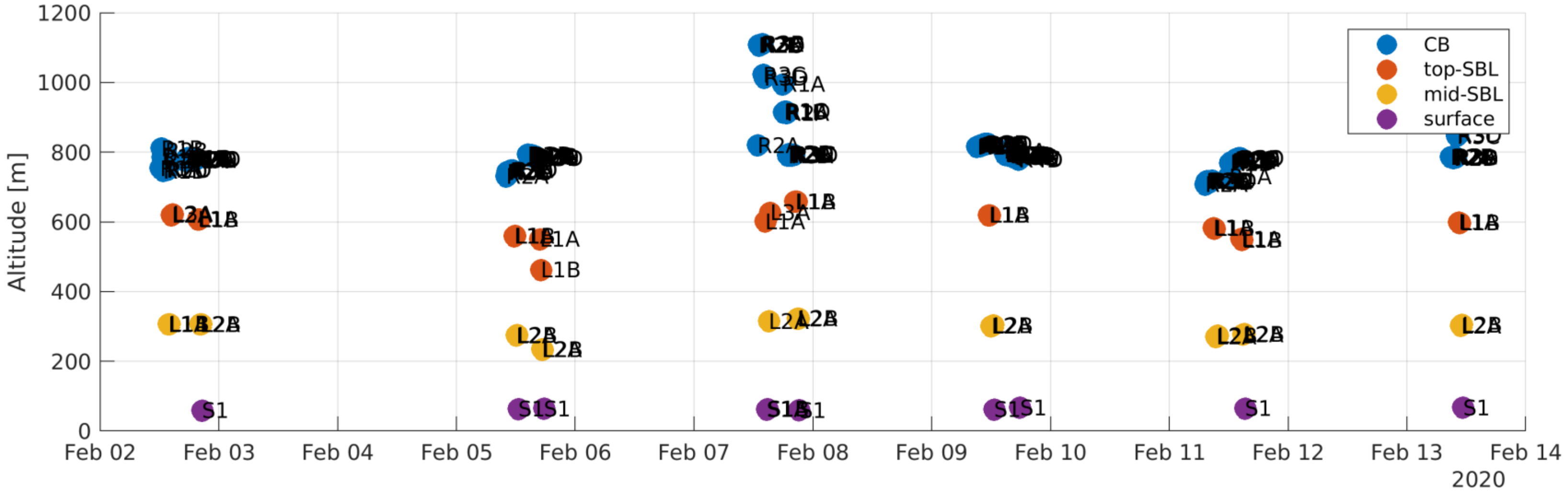
EUREC4A ATR-32 datasets

RF09 – RF19 longlegs

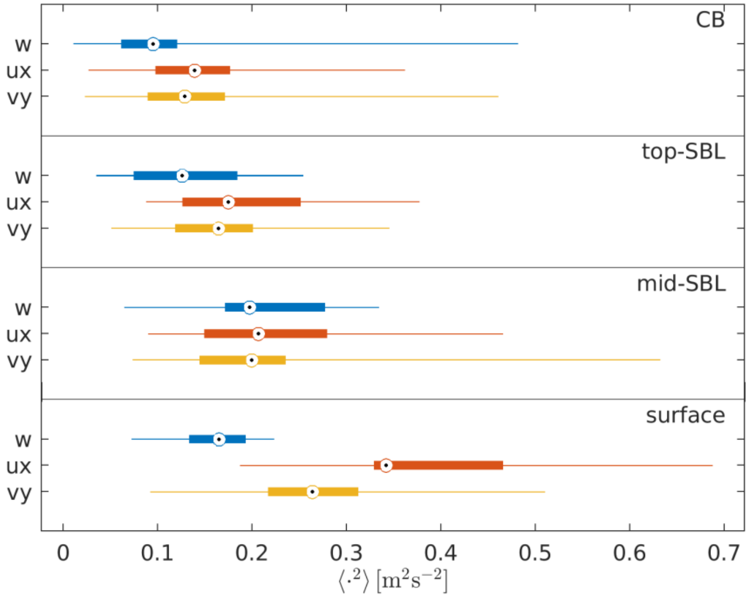
- Lothon, M. & Brilouet, P. (2020): *SAFIRE ATR42: Turbulence Data 25 Hz* (L3 v1.9)
- Bony, S., Brilouet, P. & Aemisegger, F. (2021): *SAFIRE ATR42: Flights segmentation* (v1.9)
- Coutris, P. (2021): SAFIRE ATR42: *PMA/Cloud composite dataset* (v1)

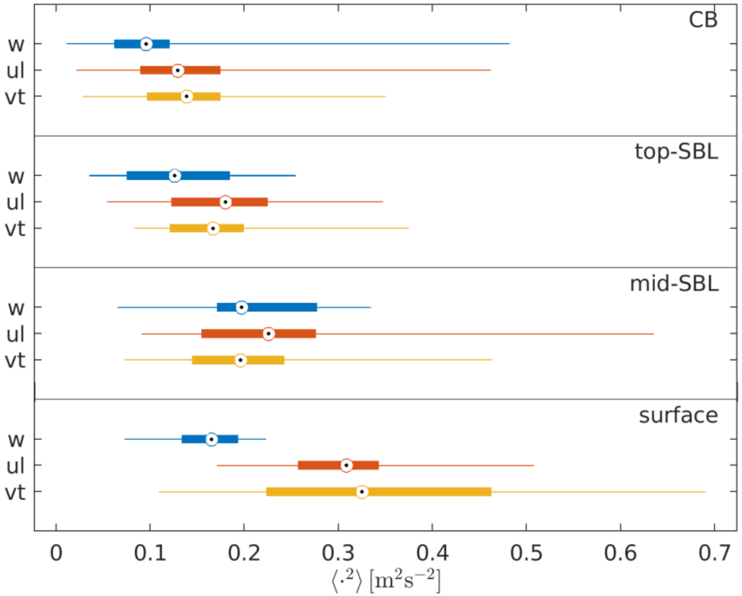
described in data papers: Bony et al. 2022, Brilouet et al. 2021

Level	#	Av length [km]
cloud-base	116	54.4
top-SBL	20	62.1
mid-SBL	19	55.8
surface	10	40.6



Segment-wide parameters: velocity variance

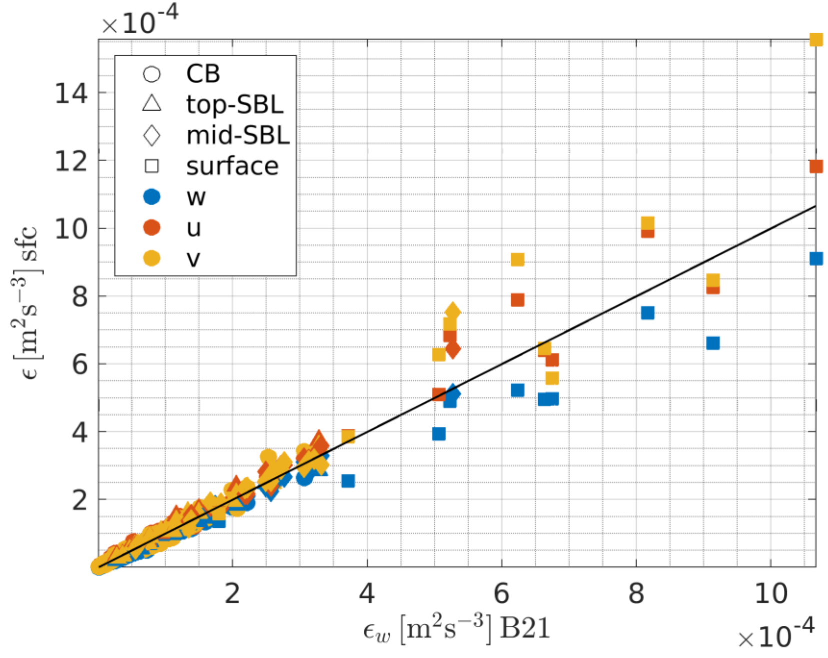




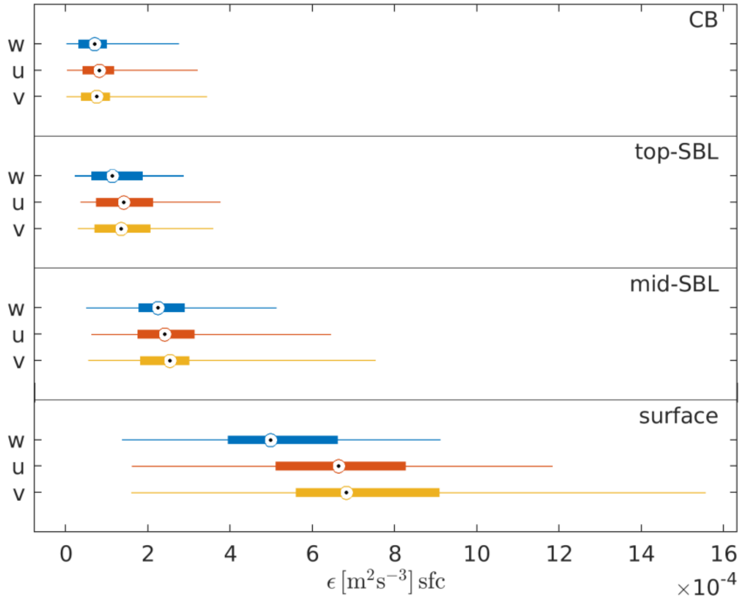
ux, vy – longitudinal and transverse with respect to aircraft
ul, vt – longitudinal and transverse with respect to mean wind

dot – median value
box – interquartile range
whisker – entire range

Segment-wide parameters: dissipation rate

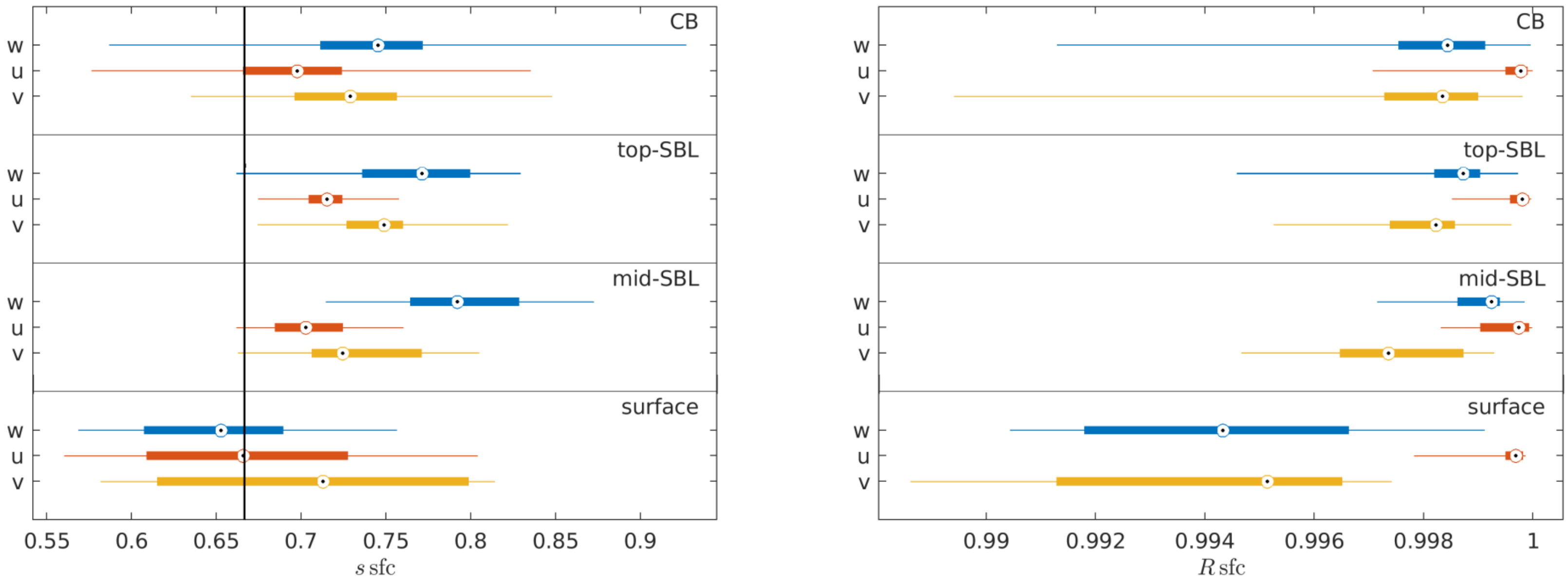


Comparison with Brilouet et al. 2021



dot – median value
box – interquartile range
whisker – entire range

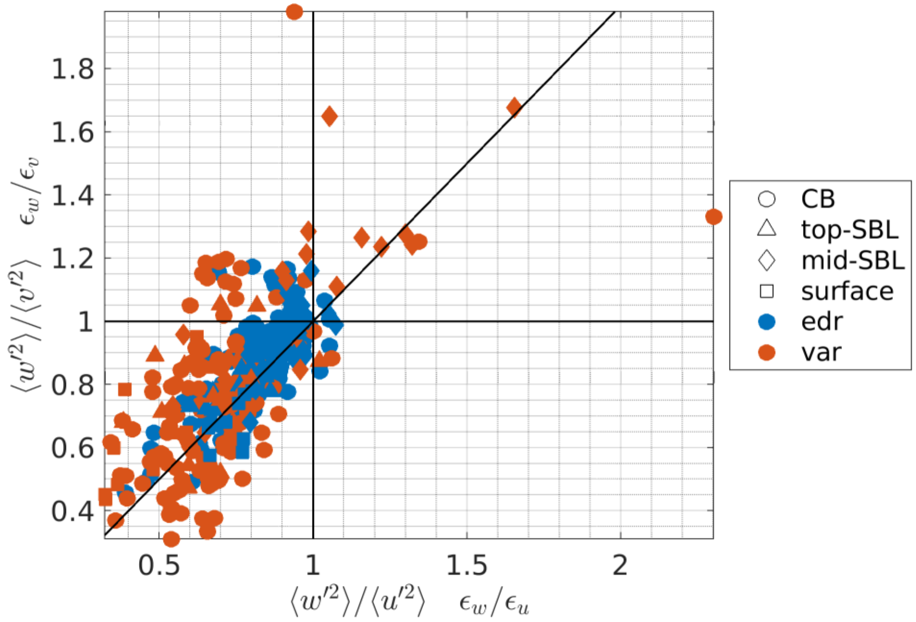
Segment-wide parameters: inertial range scaling



fitting in the range 8 - 80 m

dot – median value
box – interquartile range
whisker – entire range

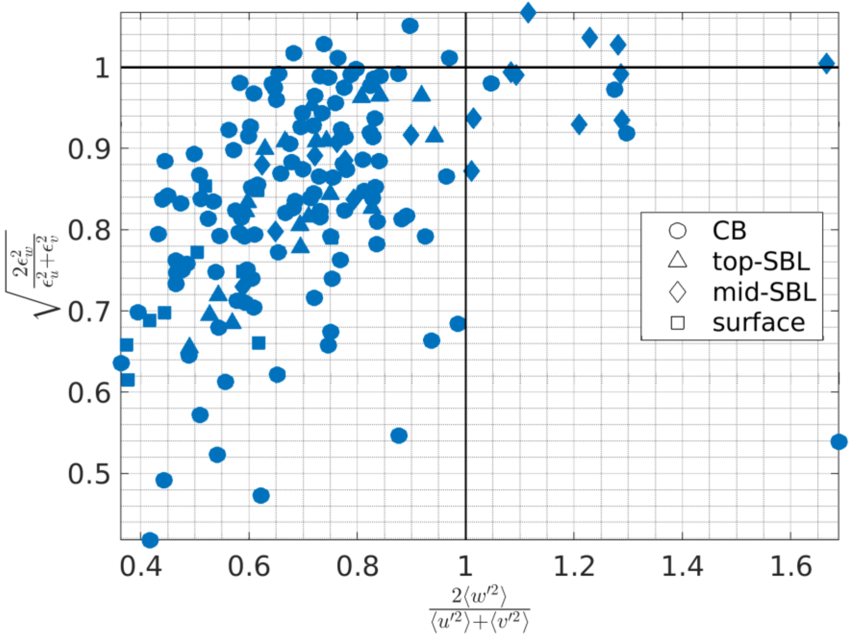
Segment-wide parameters: anisotropy

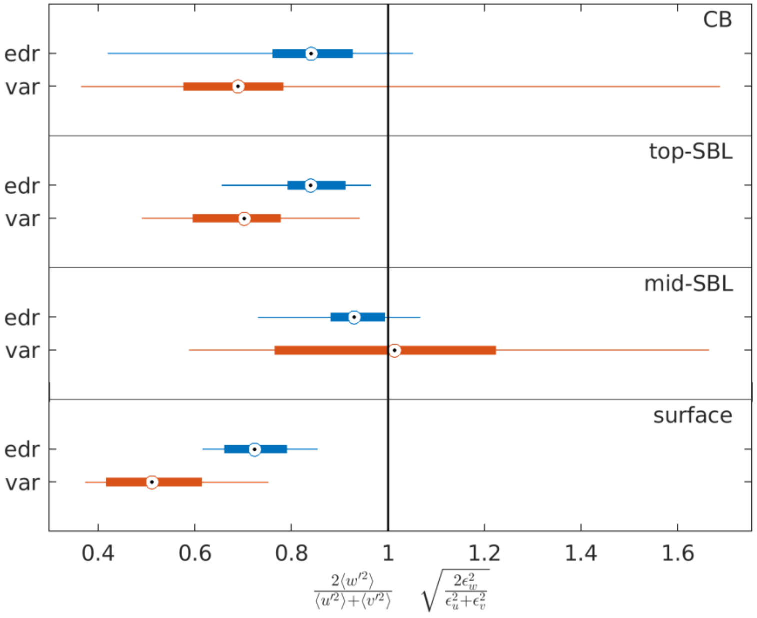


Horizontal fluctuations often prevail over vertical.
Longitudinal and lateral are mostly in balance.

Variance – dominant contribution of large eddies
Dissipation – contribution of inertial range eddies

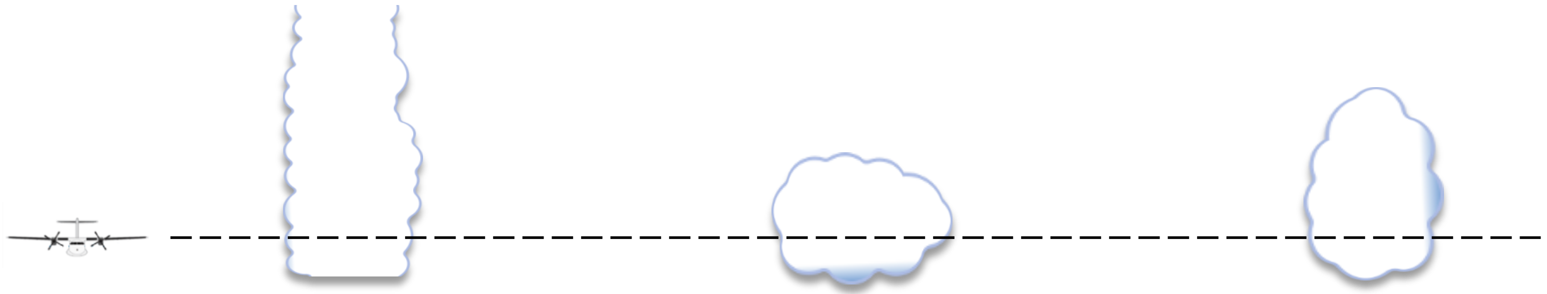
Segment-wide parameters: anisotropy





Mid SBL is close to isotropy, horizontal fluctuations prevail at other levels.
Large eddies are often more anisotropic than inertial range eddies.

Local parameters. What is the turbulence inside and outside clouds?

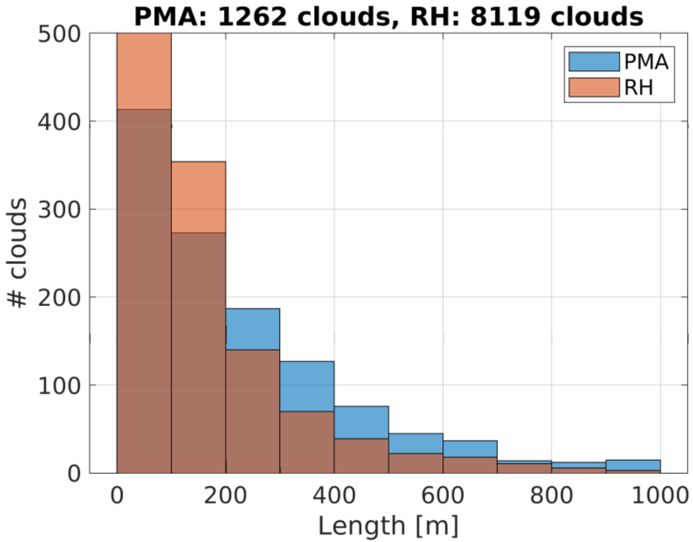


PMA cloud mask

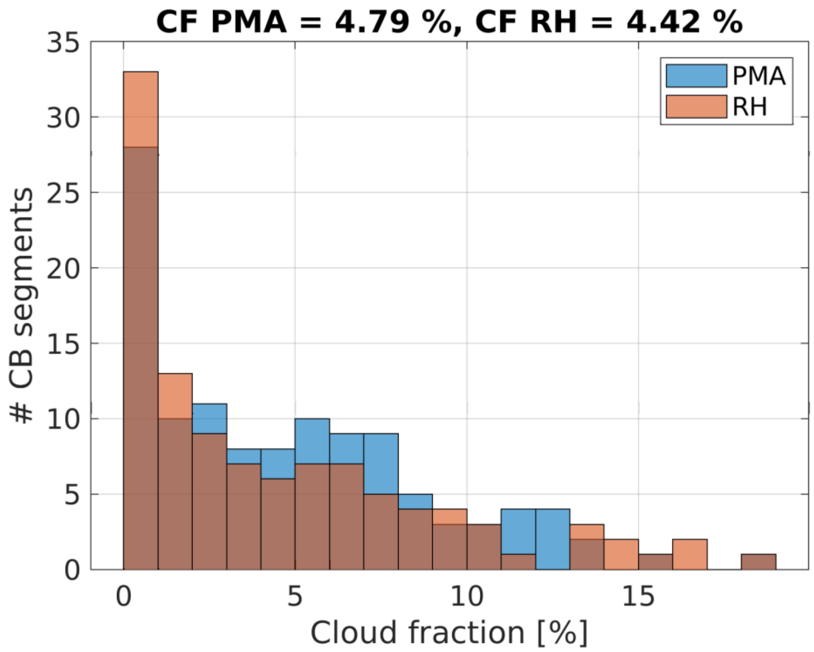
- CDP-2 + 2D-S composite in dataset Coutris (2021)
- $LWC|_{2\ \mu m < D < 90\ \mu m} > 0.01\ \frac{g}{m^3}$
- available at 1 Hz, i.e. ~100 m resolution

RH cloud mask

- following Bony et al. 2022: $x = x_{mean} + x_{det}$
- $RH > 98\ \%$
- available at 25 Hz, i.e. ~4 m resolution



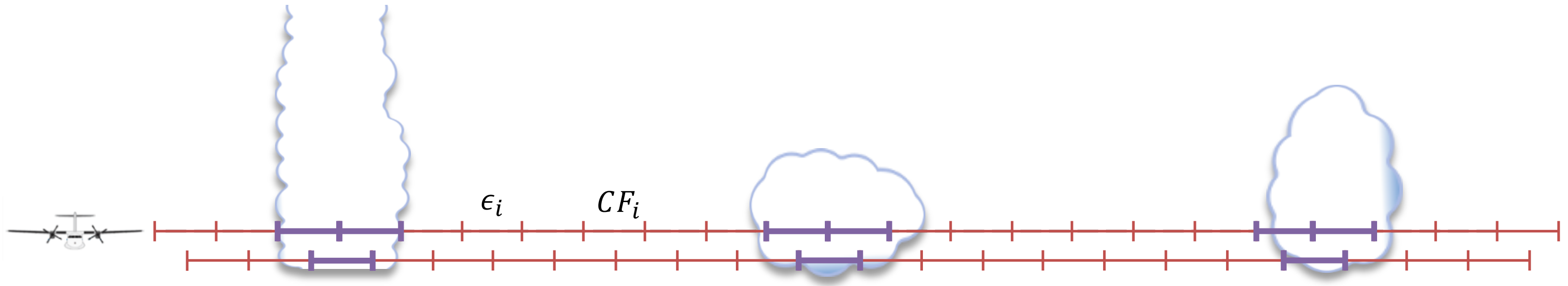
Where is the cloud?



%		upPMA		
		true	false	nan
RH	true	2.17	1.96	0
	false	2.04	87.3	0
	nan	0.58	5.94	0

upPMA – PMA 1 Hz mask interpolated at 25 Hz

How to sample turbulence in small clouds?

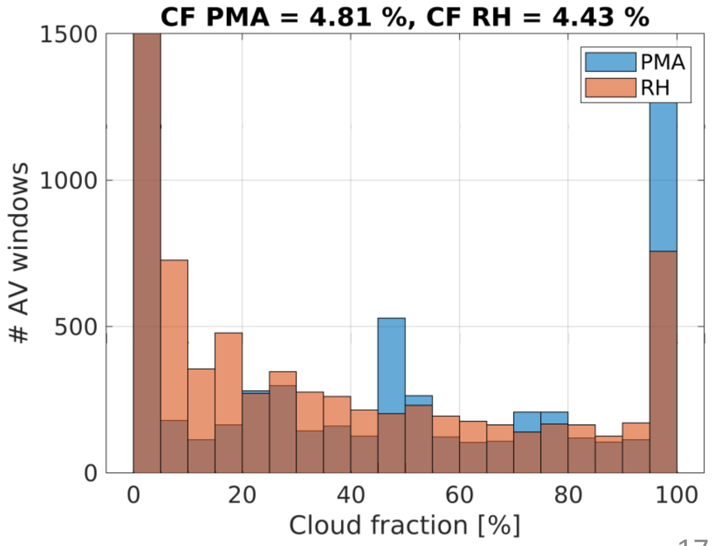


Define averaging windows of 200 m (~50 pts) overlapping by ½ length.

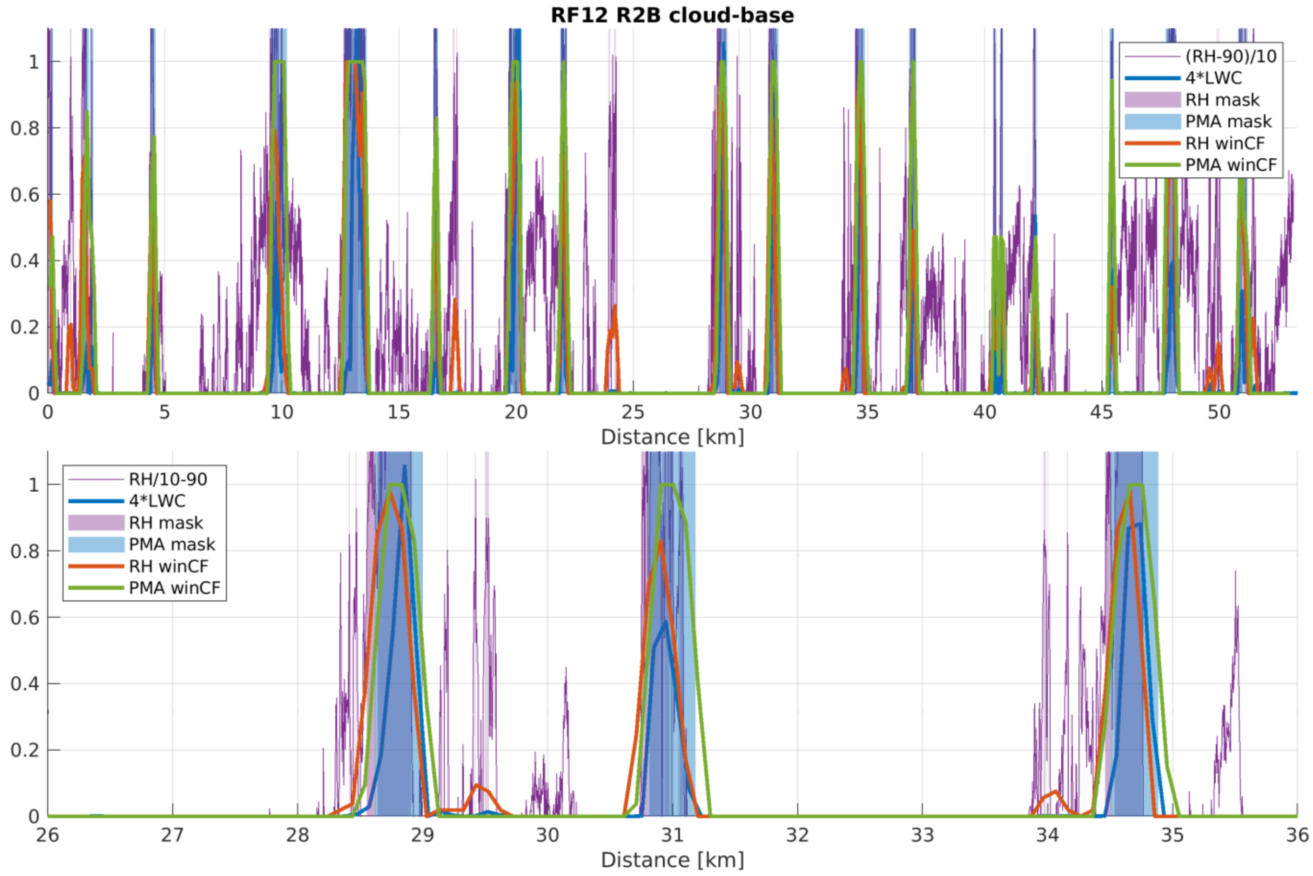
Estimate „local" turbulence parameters inside those windows.

Estimate cloud fraction in each window using RH or upPMA cloud mask.

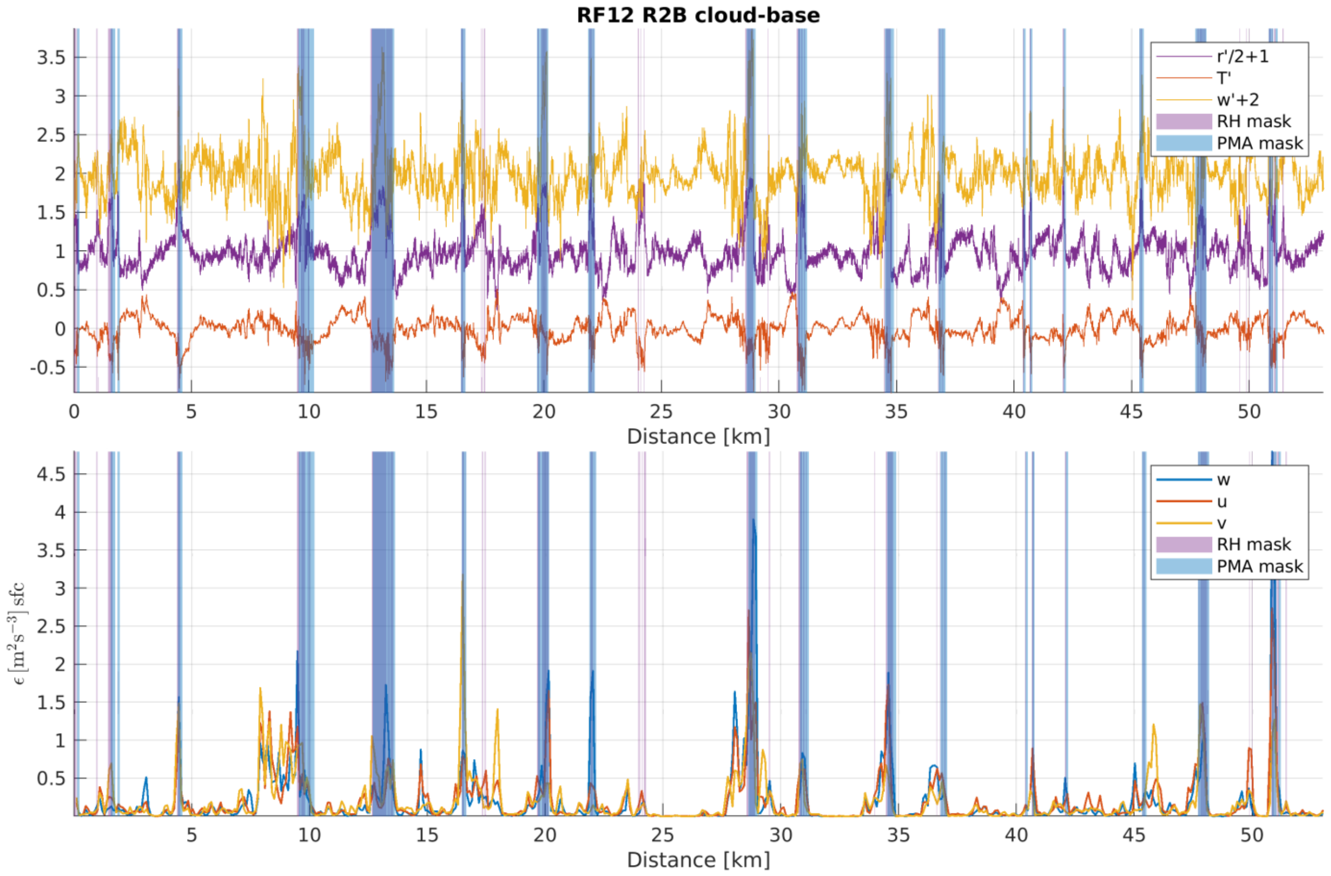
Consider windows with CF>2/3 as cloudy whereas CF=0 as clear-air.



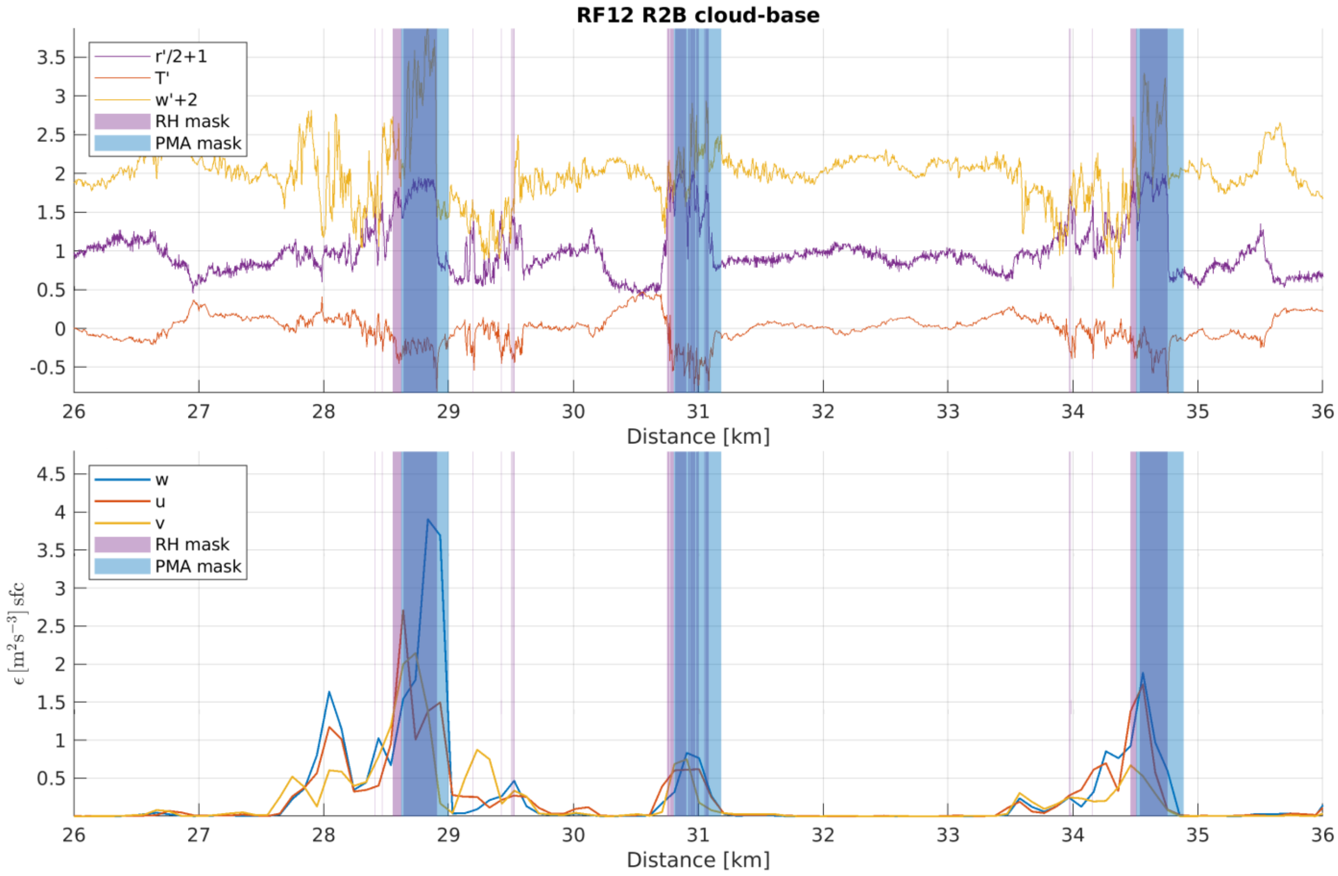
Construction of averaging windows



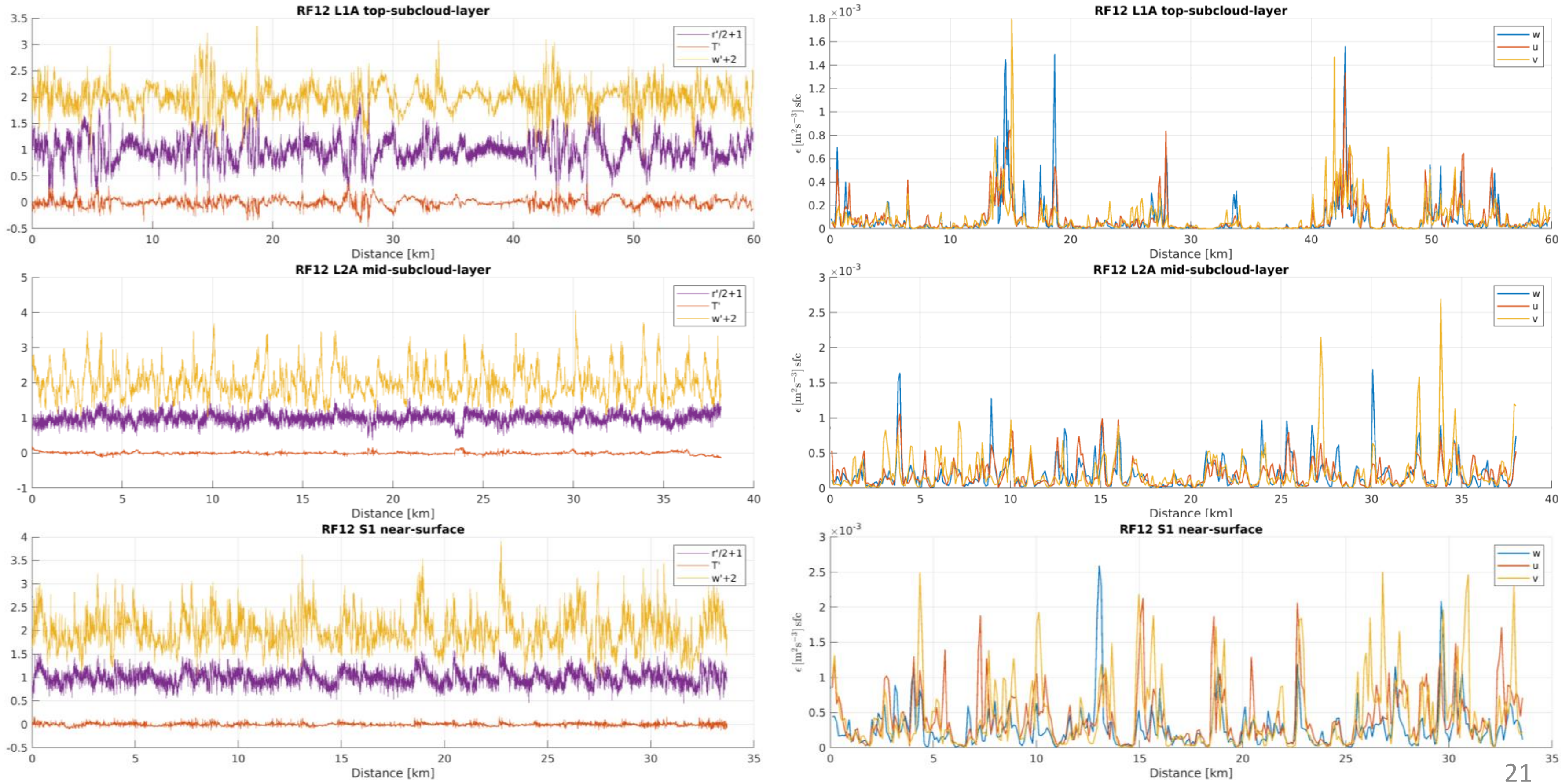
Local parameters: example



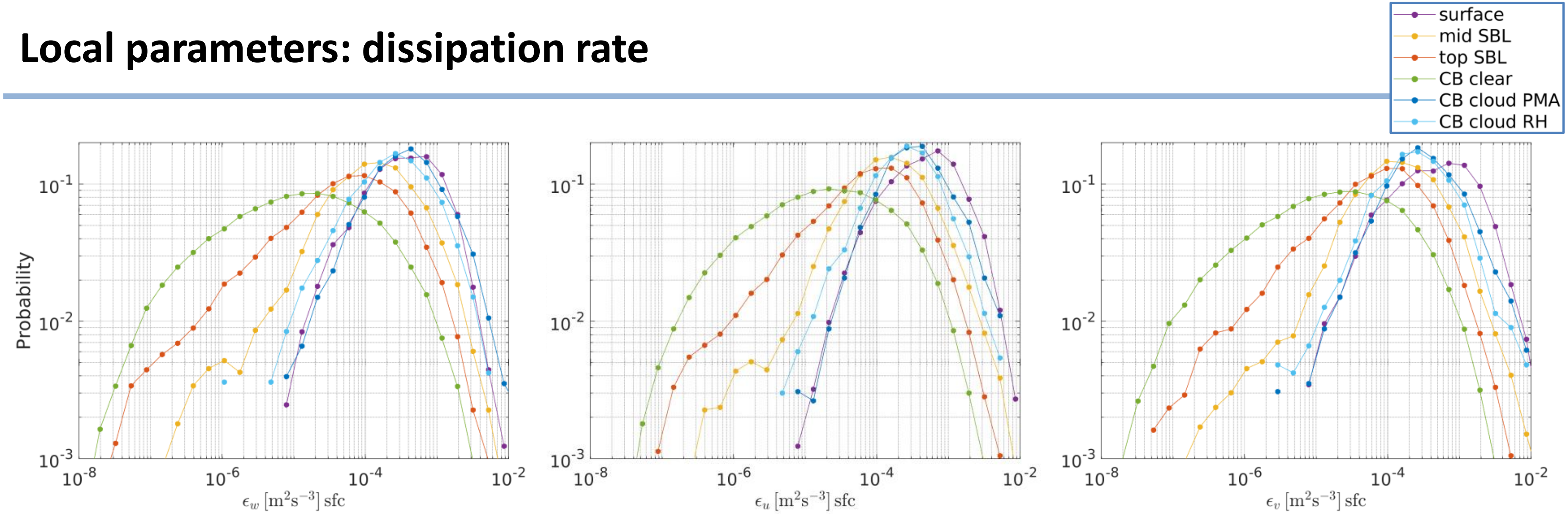
Local parameters: example (zoom)



Local parameters: examples at other levels

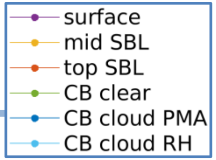


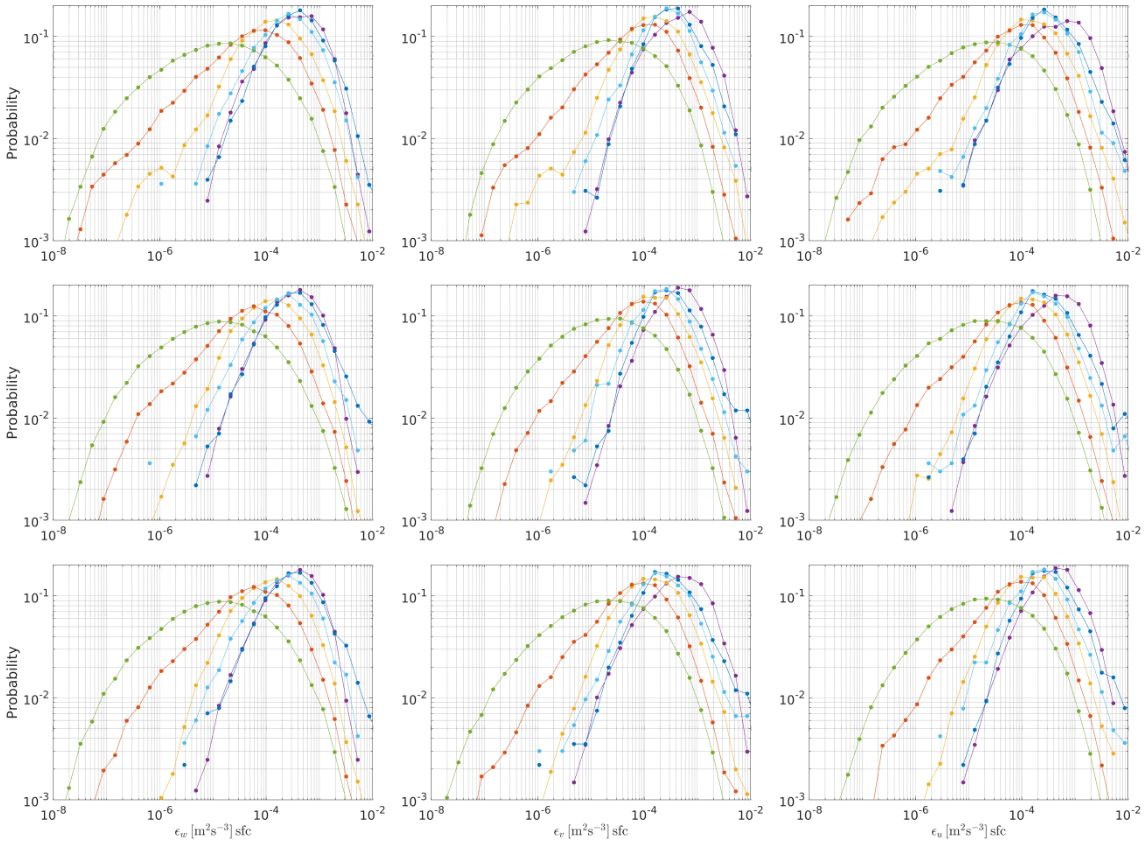
Local parameters: dissipation rate



$[\mathrm{cm^2s^{-3}}]$	surface	mid SBL	top SBL	CB clear	PMA cloud	RH cloud
ϵ_w	3.25 ± 3.85	1.12 ± 1.72	0.43 ± 0.85	0.11 ± 0.24	3.35 ± 4.27	2.17 ± 2.99
ϵ_u	4.27 ± 5.04	1.33 ± 1.88	0.62 ± 1.09	0.17 ± 0.35	3.27 ± 3.68	2.33 ± 3.40
ϵ_v	4.11 ± 5.58	1.25 ± 1.87	0.56 ± 1.03	0.15 ± 0.32	2.95 ± 3.76	2.25 ± 3.01

Local parameters: flight2flight normalization





Simple accumulation of values from different flights

„Offset” normalization

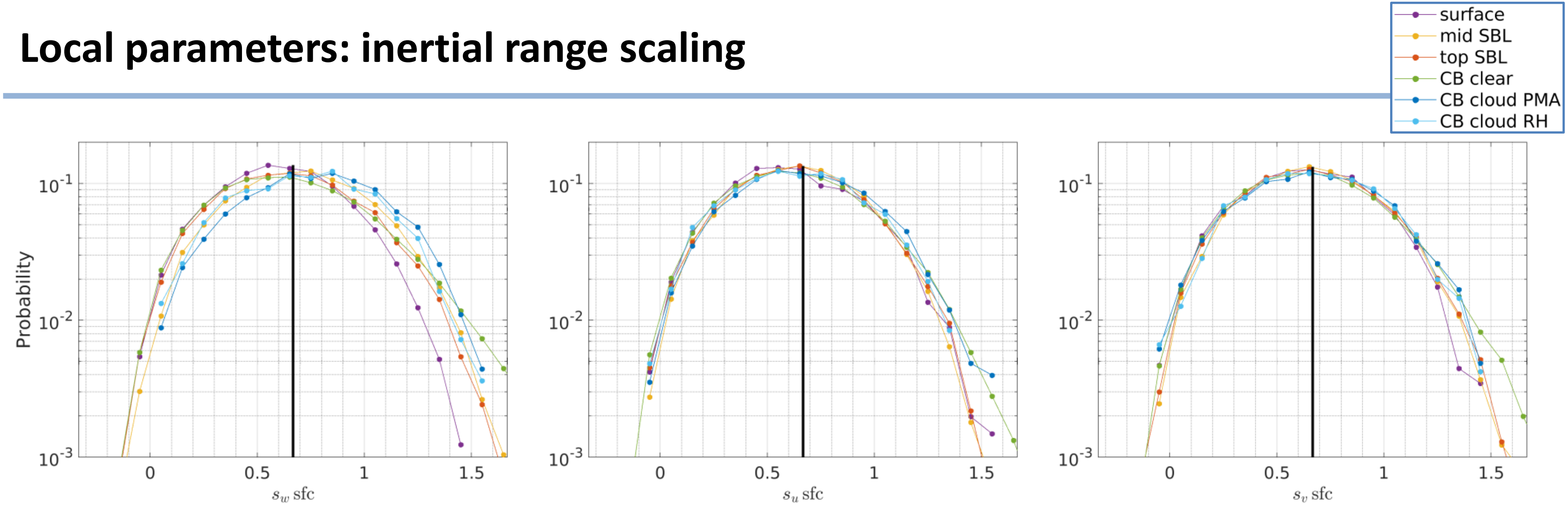
$$\widetilde{x_f^i} = x_f^i - \bar{x}_f^{ref} + \bar{\bar{x}}^{ref}$$

„Gain” normalization

$$\widetilde{x_f^i} = x_f^i \bar{\bar{x}}^{ref} / \bar{x}_f^{ref}$$

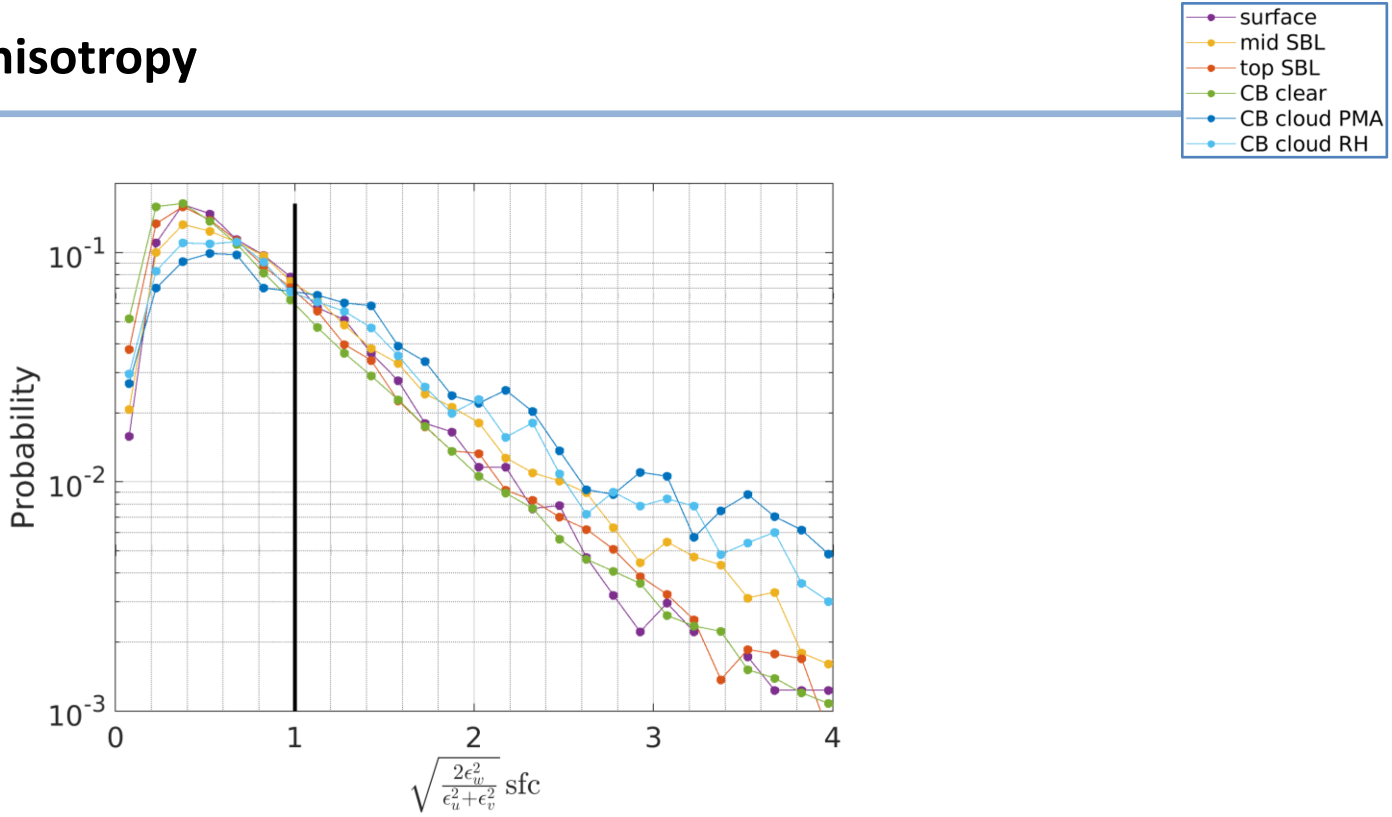
x_f^i - value in *i*-th averaging window of flight *f*
$\bar{x}_f^{ref}$ - mean at reference level in flight *f*
$\bar{\bar{x}}^{ref}$ - mean at reference level over all flights

Local parameters: inertial range scaling



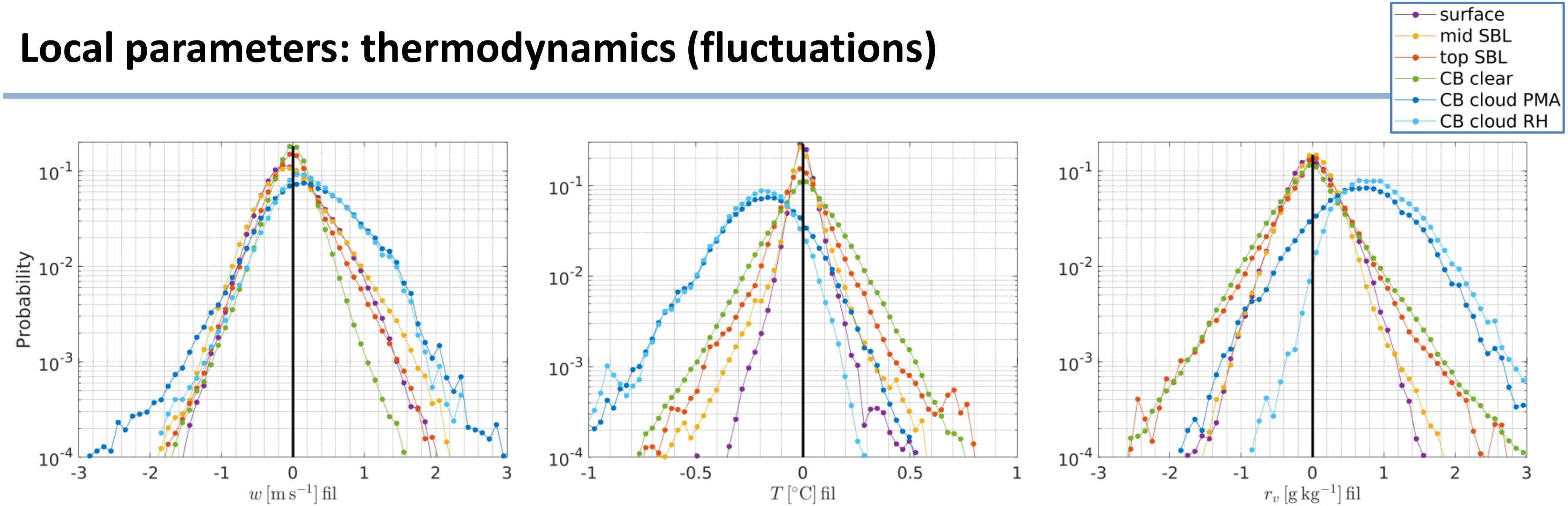
	surface	mid SBL	top SBL	CB clear	PMA cloud	RH cloud
s_w	0.62 ± 0.28	0.71 ± 0.31	0.66 ± 0.31	0.67 ± 0.34	0.77 ± 0.31	0.73 ± 0.31
s_u	0.62 ± 0.29	0.64 ± 0.28	0.64 ± 0.29	0.64 ± 0.31	0.67 ± 0.30	0.64 ± 0.30
s_v	0.64 ± 0.29	0.67 ± 0.29	0.66 ± 0.30	0.67 ± 0.32	0.67 ± 0.31	0.67 ± 0.30

Local parameters: anisotropy



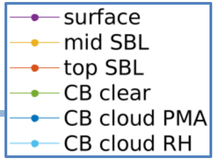
	surface	mid SBL	top SBL	CB clear	PMA cloud	RH cloud
A_ϵ	0.86 ± 0.67	1.02 ± 0.90	0.86 ± 0.82	0.82 ± 0.94	1.31 ± 1.17	1.15 ± 1.08

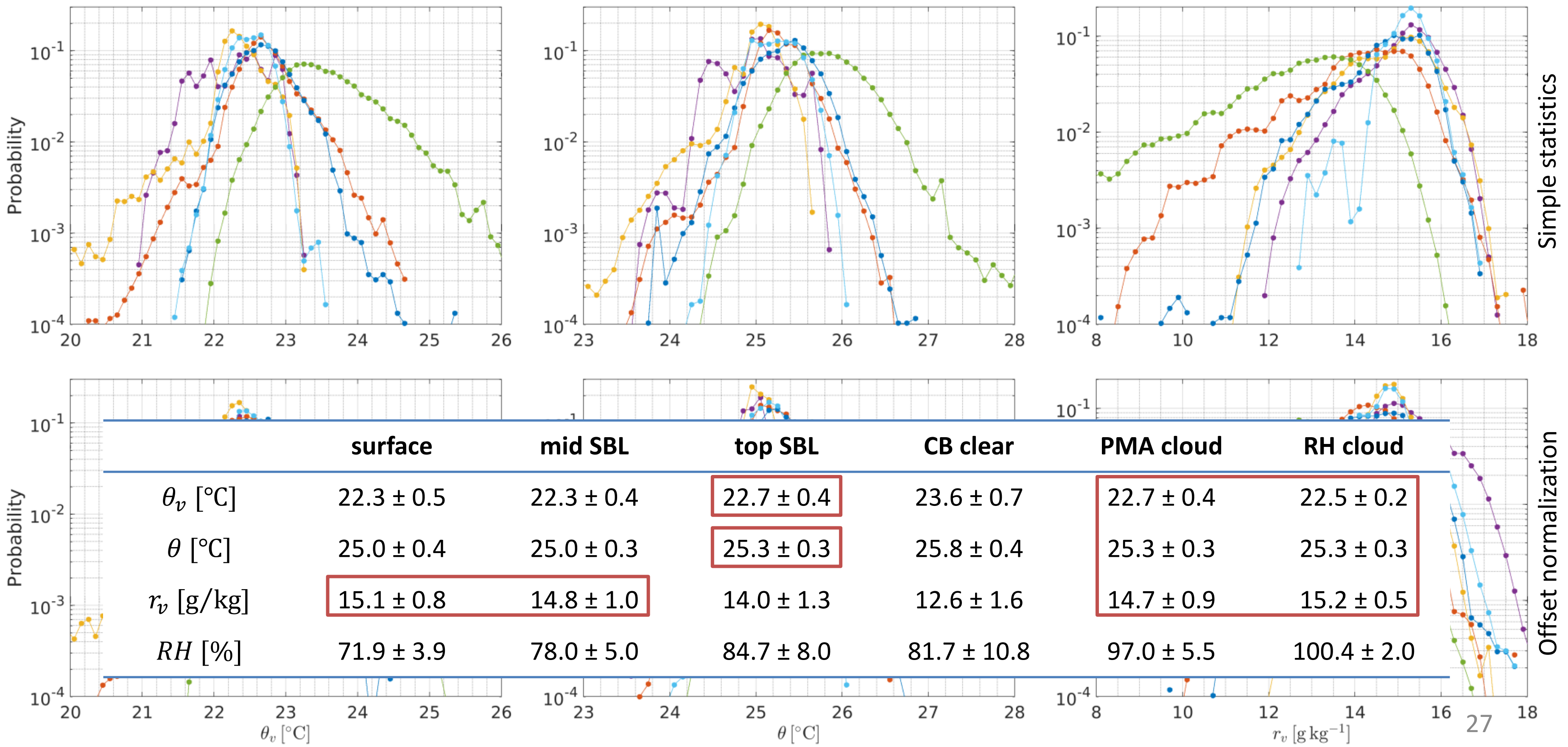
Local parameters: thermodynamics (fluctuations)



	CB clear	PMA cloud	RH cloud
w' [m/s]	-0.013 ± 0.280	0.25 ± 0.62	0.28 ± 0.51
T'[℃]	0.009 ± 0.155	-0.18 ± 0.18	-0.21 ± 0.16
r_v' [g/kg]	-0.033 ± 0.533	0.69 ± 0.66	0.95 ± 0.56

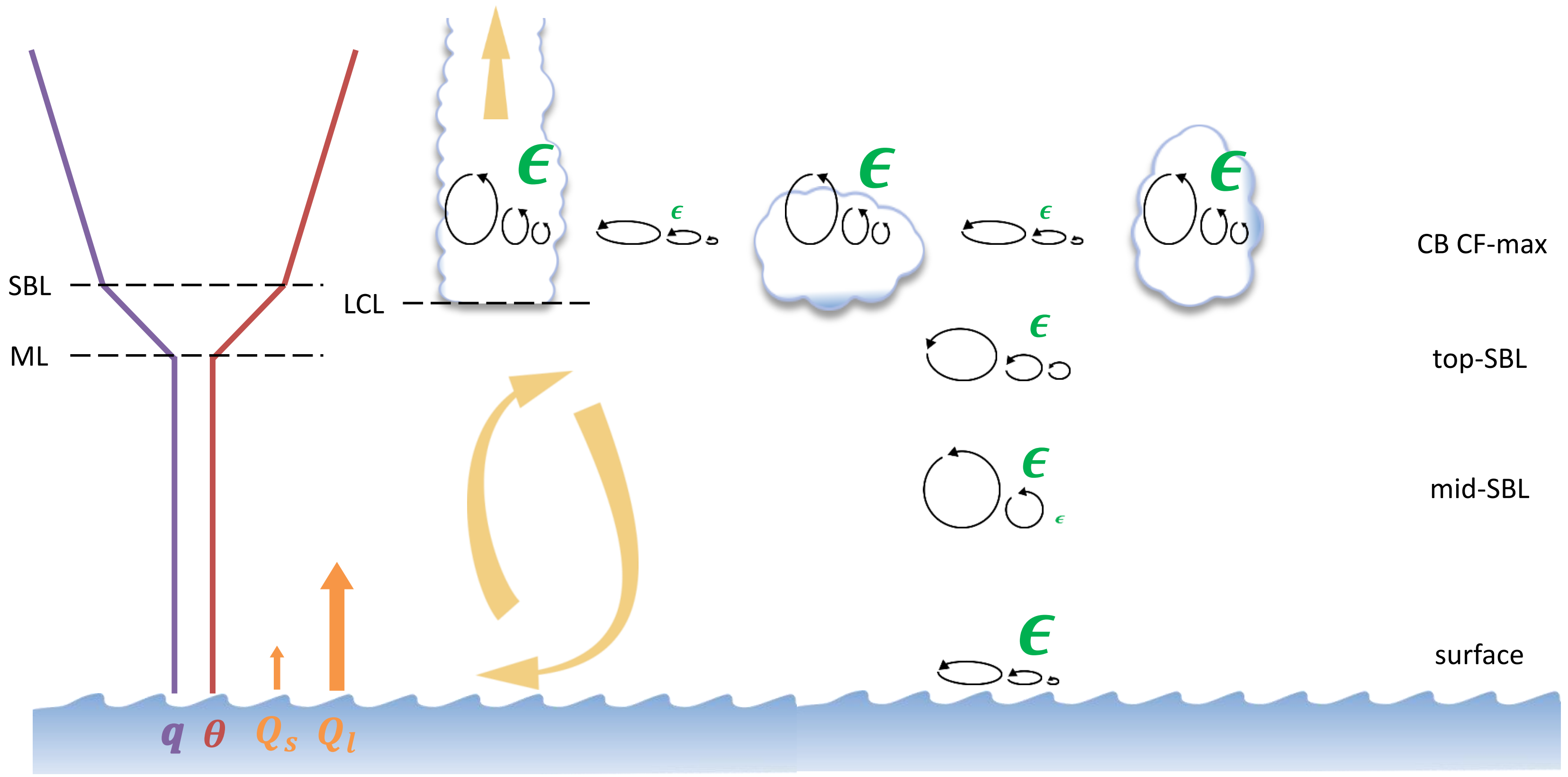
Local parameters: thermodynamics





	surface	mid SBL	top SBL	CB clear	PMA cloud	RH cloud
θ_v [°C]	22.3 ± 0.5	22.3 ± 0.4	22.7 ± 0.4	23.6 ± 0.7	22.7 ± 0.4	22.5 ± 0.2
θ [°C]	25.0 ± 0.4	25.0 ± 0.3	25.3 ± 0.3	25.8 ± 0.4	25.3 ± 0.3	25.3 ± 0.3
r_v [g/kg]	15.1 ± 0.8	14.8 ± 1.0	14.0 ± 1.3	12.6 ± 1.6	14.7 ± 0.9	15.2 ± 0.5
RH [%]	71.9 ± 3.9	78.0 ± 5.0	84.7 ± 8.0	81.7 ± 10.8	97.0 ± 5.5	100.4 ± 2.0

Small-scale turbulence in trade-wind ABL - summary



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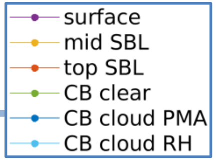
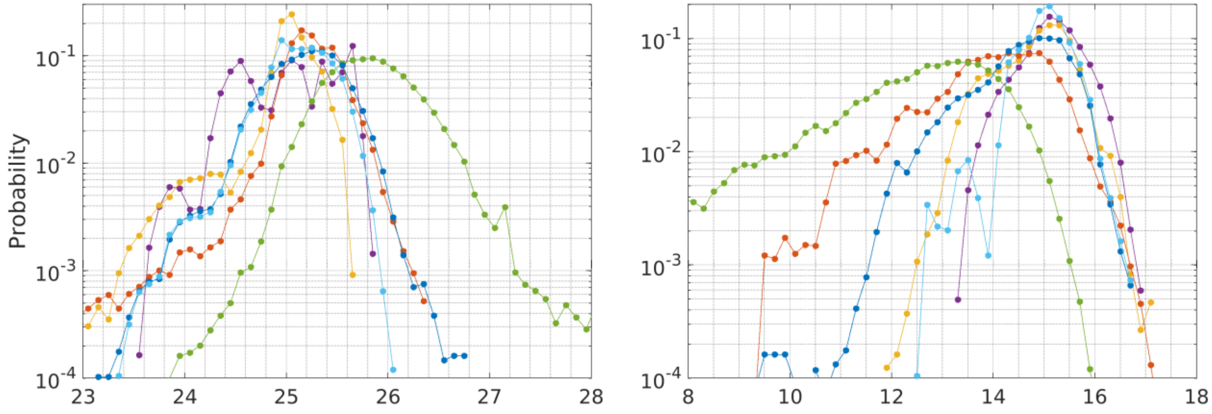
Local parameters: conserved variables





Simple statistics

	surface	mid SBL	top SBL	CB clear	PMA cloud	RH cloud
θ_l [°C]	25.0 ± 0.5	25.0 ± 0.4	25.2 ± 0.4	25.8 ± 0.5	25.2 ± 0.4	25.1 ± 0.3
θ [°C]	25.0 ± 0.4	25.0 ± 0.3	25.3 ± 0.3	25.8 ± 0.4	25.3 ± 0.3	25.3 ± 0.3
q_t [g/kg]	15.1 ± 0.6	14.8 ± 0.7	13.9 ± 1.2	12.5 ± 1.6	14.6 ± 0.9	15.0 ± 0.5
r_v [g/kg]	15.1 ± 0.8	14.8 ± 1.0	14.0 ± 1.3	12.6 ± 1.6	14.7 ± 0.9	15.2 ± 0.5