

# Authors' Final Response

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We are grateful to all the reviewers for the insightful comments and suggestions on our manuscript. We respond to them in detail below. Reviewers' comments are given in black, our answers in blue. The responses mention specific corrections which were applied as the result of reviewers' suggestions. Next, we explain minor corrections introduced by ourselves. We also attach the full revised manuscript with all the changes marked (generated with latexdiff).

## Response to the Anonymous Referee #1

Because we had responded to the reviewer before other reviews arrived, some minor details in the quoted passages of the manuscript has been modified. Please see the revised manuscript for the final version.

## General comments

While it is longer than most manuscripts that I review, I'm not sure that it can be substantially shortened without omitting important information.

We considered this issue before and reached the same conclusion that presenting the entire material together is of advantage for understanding the differences in turbulence character between coupled and decoupled STBL cases. Importantly, we designed most of the figures so that they fit into one column of the ACP layout. When typeset in two-column, the manuscript contains 24 pages, with last four occupied by the tables and references.

## Specific comments

1. Lines 43–45: Could a reduction in cloud-top LW cooling due to an overrunning cloud layer at somewhat higher altitude also contribute to decoupling?

During the day, such an overrunning cloud layer would also reduce the solar heating of stratocumulus top. The solar heating is known to promote STBL decoupling. It is not clear to us which effect is dominant. We speculate it might depend on the height of the upper cloud and its radiative properties. During the night, the net cooling would be indeed reduced which itself favors decoupling, but on the other hand this hinders the entrainment and growth of the boundary layer. Therefore, the relative importance of those effects needs to be quantified. Unfortunately, we are not aware of the

relevant studies supporting the mechanism suggested by the reviewer. Once we find such, we will update the introduction of our manuscript accordingly.

Such mechanism was most likely not relevant for the STBL decoupling observed in flight #14. During the flight on 18 July 2017, no overlying cloud layer was reported by the scientists onboard the helicopter. In the substantial region around the operation area, the satellite products derived from MODIS onboard Aqua (NASA Worldview portal) indicate cloud top temperature in the class of 285-290 K and cloud top height in the class of 800-1600 m, both consistent with our observations of stratocumulus top (c.f. Fig. 6).

2. Line 106: LEGs are described as being 10 km long, but the time intervals shown on Fig. 2 seem too short at the nominal flight speed of 20 m/sec. I would prefer to see lengths and altitudes of the LEGs included in a table. Among other things, this is relevant to the question of flux sampling error (see comment further down).

The horizontal segments flown by the platform were indeed at least 10 km long. However, the manual segmentation resulted in shorter LEGs selected for the analysis as pointed out by the reviewer. In fact, LEGs are between 3.5 and 12 km long (see Table 1). This segmentation was performed in somewhat conservative manner in order to ensure that there is no potential influence of turns or pendulum-like motion of the payload on the measurement of turbulent fluctuations. This issue also relates to the next comment concerning helicopter rotor downwash.

Our description of the segmentation was incomplete with respect to the lengths. After correction it reads:

Segments of two types were selected from the measurement records: profiles (PROFs) and horizontal legs (LEGs). For convenience, they are ordered according to their time of execution and referred to as PROF1-PROF5 and LEG1-LEG5, for each flight. The segmentation was done manually so that the influence of sharp turns and pendulum-like motion of the payload is avoided. This resulted in the reduced length of the LEGs, between 3.5 and 12 km. LEGs were flown with TAS of 15-20  $\text{m s}^{-1}$  and some minor displacements in vertical are unavoidable for the payload on a 170 m long rope. The mean altitudes and exact lengths are listed in Table 1. PROFs are in fact slanted with an ascent or descent rate of about 3-5  $\text{m s}^{-1}$  and TAS  $\sim 20 \text{ m s}^{-1}$ . The horizontal component of motion is necessary to avoid the downwash of the helicopter affecting wind and turbulence measurements on ACTOS.

3. The helicopter used weighs somewhere around 2000 kg and imparts substantial downward momentum and turbulent kinetic energy to the environment directly below it. In fact, rotor downwash speeds a short distance below the helicopter are probably around 30 m/sec, and the area of influence expands considerably with distance below the aircraft (albeit with reduced velocities). With that in mind, I would have liked to see more discussion, including any relevant references, in support of the assumption that a 20 m/sec forward speed is sufficient to avoid any influence by the rotorwash on the ACTOS package suspended 150 m below the helicopter, taking into account as well that the package probably trails behind the helicopter by some distance during forward flight.

**Table 1.** Mean altitude and length of the LEGs.

<b>Flight #5</b>	<b>LEG5</b>	<b>LEG4</b>	<b>LEG3</b>	<b>LEG2</b>	<b>LEG1</b>
Height [m]	307	553	819	1079	2018
Length [km]	5.44	5.51	7.93	3.94	6.25

<b>Flight #14</b>	<b>LEG1</b>	<b>LEG2</b>	<b>LEG3</b>	<b>LEG5</b>	<b>LEG4</b>
Height [m]	143	287	448	992	2021
Length [km]	8.11	11.92	7.10	4.79	3.49

These issues are definitively worth to discuss and essential for high resolution turbulence observations with ACTOS. There are two major points to be considered:

- (a) A helicopter has two completely different modes of operation (i) hovering and (ii) forward motion (and a transition phase at a true airspeed of a few meters per second which we do not consider here). During take-off the helicopter is in hovering mode and you can see (and feel) the influence of the downwash even if the helicopter is 150 m above ACTOS - this is particularly true if the wind is weak. However, on forward motion the complete rotor blade area is tilted and the downwash is deflected backwards. By the way, that is the reason why a Pitot static tube at the nose of the helicopter provides precise true airspeed even less than 2 m below the rotor blades.
- (b) Any possible influence of the downwash should be visible in a power spectrum. This has been evaluated by colleagues operating a similar helicopter towed system called Helipod (Muschinski et al., 2001). They operate at 40 m/s with a 15 m rope but apply a 5-hole probe to sample turbulence. They see a sharp signal in the spectrum due to the sound waves.

This discussion with even more details has been published in the previous publication about ACTOS (Siebert et al., 2006a) which has been cited at the beginning of the instrumental part (Sec 2.2.) of our manuscript. Therefore, we suggest to avoid a repetition of this discussion here but included a sentence for interested readers:

More details about measuring turbulence below a helicopter can be found in Siebert et al. (2006a).

4. I believe there should be explicit discussion of sampling error, and its relationship to flight leg length, in connection with the turbulent flux measurements. One newly published paper that seems relevant is Petty, G. W.: Sampling error in aircraft flux measurements based on a high-resolution large eddy simulation of the marine boundary layer, *Atmos. Meas. Tech.*, 14, 1959–1976, <https://doi.org/10.5194/amt-14-1959-2021>, 2021.

We have already performed a comprehensive analysis of sampling error using the methods given by Lenschow et al. (1994), hereafter L94, with respect to our LEG measurements of turbulent fluxes as well as turbulent variances. However,

taking into account the length of the manuscript, we decided to only show the standard deviation among the relevant values derived separately for seven subsegments (Std7, see sec. 4) because the same method can be applied to other variables in our work, in particular turbulence parameters (e.g. dissipation rate or anisotropy ratios) for which the rigorous and practical formulas for systematic/random errors are not available. Moreover, we found that Std7 is of the same order as random error (L94ran), exceeding it in most of the cases, while systematic error (L94sys) is significantly smaller. The detailed analysis is intended to be covered in the doctoral dissertation of Jakub L. Nowak. Here, we briefly describe the procedure and present the results.

For each variable  $x$  out of  $u$ ,  $\theta_v$ ,  $q_v$ ,  $T$ , integral lengthscales  $L_x$ ,  $L_{wx}$ ,  $L_f$  (corresponding to autocovariance of  $x'$ , covariance of  $w'$  and  $x'$ , autocovariance of the product  $w'x'$ , respectively) were estimated with the procedure described in sec. 4.5 of our manuscript. Accordingly, we calculated correlation coefficient  $r_{wx}$  of  $w'$  and  $x'$ . Those values are listed in Tables 2 and 3 for flights #5 and #14, respectively.

For variances, systematic error was estimated using Eq. (14) while random error using Eq. (36) of L94. In case of the third moment of vertical velocity, the coefficient  $a$  was found by solving their Eq. (20) and then its value was applied to estimate systematic error according to their Eq. (21). Random error of  $\langle w'^3 \rangle$  was estimated according to Eq. (B40) of Lenschow et al. (1993). The errors are compared with Std7 in Tables 4 and 5 for flights #5 and #14, respectively.

For fluxes, systematic error was estimated with Eq. (30) and random error with Eq. (48) of L94. The latter is also the equation upon which Petty (2021) builds his analysis. He proved this equation to be very accurate at predicting random error for flight tracks of the length relevant for our LEGs. The errors are compared with the subsegment variability in Tables 6 and 7 for flights #5 and #14, respectively.

Following the reviewer's request we briefly discuss the issue of the sampling errors in sec. 4.1 and 4.2 of the manuscript:

The accuracy of the results is limited by the length of the LEGs. Based on the estimates obtained with the methods of Lenschow et al. (1994), in the boundary layer the variances are subject to the systematic sampling error of about 5 % and the random error of about 20 %. In case of  $\langle w'^3 \rangle$ , those errors are accordingly larger (order of 10 % and 100 %, respectively, unless  $\langle w'^3 \rangle$  is not very close to zero). Importantly, in the plots we provide the variability among subsegments because it can be estimated for other variables as well, in particular turbulence parameters, and it was found to be of the same order as the total sampling error, in most cases larger than it (not shown).

Similarly to variances, the accuracy of the fluxes obtained with eddy correlation is limited by the length of the LEGs. In the boundary layer, systematic error was estimated for about 5-10 % while random error for about 50 % (Lenschow et al., 1994), unless the flux does not vanish. The subsegment variability (marked with errorbars in the plots) is in most cases larger than the total sampling error.

**Table 2.** Integral scales and correlations in flight #5.

Variable		LEG5	LEG4	LEG3	LEG2	LEG1
Height [m]		307	553	819	1079	2018
Length [km]		5.44	5.51	7.93	3.94	6.25
$w'$	$L_w$ [m]	146	120	97	112	64
$u'$	$L_u$ [m]	113	154	179	101	112
	$L_{wu}$ [m]	520	54	31	185	182
	$L_f$ [m]	80	83	39	59	46
	$r_{wu}$ [m]	-0.26	-0.20	-0.11	0.21	-0.31
$\theta'_v$	$L_{\theta_v}$ [m]	108	110	172	79	117
	$L_{w\theta_v}$ [m]	353	655	255	25	50
	$L_f$ [m]	48	59	56	37	12
	$r_{w\theta_v}$ [m]	0.30	-0.08	0.46	-0.09	-0.16
$q'_v$	$L_{q_v}$ [m]	160	136	94	120	318
	$L_{wq_v}$ [m]	157	82	200	NaN	152
	$L_f$ [m]	48	90	43	88	18
	$r_{wq_v}$ [m]	0.56	0.06	0.54	-0.00	0.09
$T'$	$L_T$ [m]	76	129	204	108	250
	$L_{wT}$ [m]	156	177	238	178	59
	$L_f$ [m]	21	46	51	30	27
	$r_{wT}$ [m]	0.27	0.29	0.55	-0.12	0.14

**Table 3.** Integral scales and correlations in flight #14.

Variable		LEG1	LEG2	LEG3	LEG5	LEG4
Height [m]		143	287	448	992	2021
Length [km]		8.11	11.92	7.10	4.79	3.49
$w'$	$L_w$ [m]	53	86	74	35	249
$u'$	$L_u$ [m]	103	111	109	105	180
	$L_{wu}$ [m]	54	88	63	64	6
	$L_f$ [m]	33	46	29	28	28
	$r_{wu}$ [m]	0.10	-0.18	-0.13	0.14	-0.00
$\theta'_v$	$L_{\theta_v}$ [m]	85	50	153	62	115
	$L_{w\theta_v}$ [m]	69	6	596	107	21
	$L_f$ [m]	19	13	71	23	12
	$r_{w\theta_v}$ [m]	0.29	0.03	-0.10	0.28	-0.16
$q'_v$	$L_{q_v}$ [m]	79	119	117	82	74
	$L_{wq_v}$ [m]	69	89	489	244	160
	$L_f$ [m]	34	60	62	35	25
	$r_{wq_v}$ [m]	0.44	0.42	0.07	0.04	0.11
$T'$	$L_T$ [m]	52	76	127	49	28
	$L_{wT}$ [m]	33	2	148	130	489
	$L_f$ [m]	29	21	20	23	14
	$r_{wT}$ [m]	0.24	0.01	0.17	0.16	0.28

**Table 4.** Statistical errors of the LEG-derived moments in flight #5 (coupled STBL): standard deviation among subsegments (Std7), systematic and random errors according to L94 (L94sys and L94ran).

Variable		LEG5		LEG4		LEG3		LEG2		LEG1	
Height [m]		307		553		819		1079		2018	
$\langle w'^2 \rangle$	[m <sup>2</sup> s <sup>-2</sup> , %]	0.212		0.104		0.162		0.004		0.006	
	Std7	0.087	41	0.018	17	0.056	35	0.001	23	0.002	29
	L94sys	0.011	5.4	0.005	4.4	0.004	2.4	0.000	5.7	0.000	2.0
	L94ran	0.049	23	0.022	21	0.025	16	0.001	24	0.001	14
$\langle w'^3 \rangle$	[10 <sup>-2</sup> m <sup>3</sup> s <sup>-3</sup> , %]	1.69		0.06		0.23		-0.01		-0.02	
	Std7	2.20	130	1.55	2658	2.12	908	0.02	182	0.02	108
	L94sys	0.23	13.4	0.01	10.9	0.01	6.1	0.00	14.3	0.00	5.1
	L94ran	3.38	200	0.99	1699	1.45	619	0.01	130	0.01	74
$\langle u'^2 \rangle$	[m <sup>2</sup> s <sup>-2</sup> , %]	0.34		0.27		0.20		0.37		0.20	
	Std7	0.10	29	0.09	32	0.03	13	0.13	34	0.10	49
	L94sys	0.01	4.2	0.02	5.6	0.01	4.5	0.02	5.1	0.01	3.6
	L94ran	0.07	20	0.06	24	0.04	21	0.08	23	0.04	19
$\langle q_v'^2 \rangle$	[10 <sup>-3</sup> g <sup>2</sup> kg <sup>-2</sup> , %]	5.4		7.8		26.4		1.4		0.0	
	Std7	1.0	18	1.6	21	17.1	65	1.3	91	0.0	18
	L94sys	0.3	5.9	0.4	4.9	0.6	2.4	0.1	6.1	0.0	10.2
	L94ran	1.3	24	1.7	22	4.1	15	0.3	25	0.0	32
$\langle T'^2 \rangle$	[10 <sup>-3</sup> K <sup>2</sup> , %]	3.3		7.5		18.4		7.3		7.8	
	Std7	0.9	26	3.0	39	8.0	43	6.3	86	3.7	47
	L94sys	0.1	2.8	0.4	4.7	0.9	5.1	0.4	5.5	0.6	8.0
	L94ran	0.6	17	1.6	22	4.2	23	1.7	23	2.2	28

**Table 5.** Statistical errors of the LEG-derived moments in flight #14 (decoupled STBL): standard deviation among subsegments (Std7), systematic and random errors according to L94 (L94sys and L94ran).

Variable		LEG5		LEG4		LEG3		LEG2		LEG1	
Height [m]		143		287		448		992		2021	
$\langle w'^2 \rangle$	[m <sup>2</sup> s <sup>-2</sup> , %]	0.106		0.076		0.047		0.054		0.004	
	Std7	0.036	34	0.027	36	0.014	30	0.012	22	0.002	35
	L94sys	0.001	1.3	0.001	1.5	0.001	2.1	0.001	1.5	0.001	14.3
	L94ran	0.012	11	0.009	12	0.007	14	0.007	12	0.002	38
$\langle w'^3 \rangle$	[10 <sup>-2</sup> m <sup>3</sup> s <sup>-3</sup> , %]	0.49		1.34		-0.21		-0.47		-0.01	
	Std7	1.33	272	0.88	66	0.53	247	0.28	59	0.02	287
	L94sys	0.02	3.3	0.05	3.6	0.01	5.2	0.02	3.7	0.00	35.7
	L94ran	0.58	119	0.59	44	0.23	105	0.27	57	0.02	295
$\langle u'^2 \rangle$	[m <sup>2</sup> s <sup>-2</sup> , %]	0.21		0.14		0.27		0.19		0.05	
	Std7	0.11	53	0.04	25	0.05	18	0.05	27	0.01	32
	L94sys	0.01	2.5	0.00	1.9	0.01	3.1	0.01	4.4	0.00	10.3
	L94ran	0.03	16	0.02	14	0.05	18	0.04	21	0.01	32
$\langle q_v'^2 \rangle$	[10 <sup>-3</sup> g <sup>2</sup> kg <sup>-2</sup> , %]	27.1		12.0		44.7		31.7		1.2	
	Std7	6.1	23	3.5	30	21.0	47	9.8	31	0.4	32
	L94sys	0.5	1.9	0.2	2.0	1.5	3.3	1.1	3.4	0.1	4.3
	L94ran	3.8	14	1.7	14	8.1	18	5.9	19	0.3	21
$\langle T'^2 \rangle$	[10 <sup>-3</sup> K <sup>2</sup> , %]	6.7		5.9		11.0		7.7		4.9	
	Std7	0.6	9	1.1	18	3.4	31	3.0	39	0.8	17
	L94sys	0.1	1.3	0.1	1.3	0.4	3.6	0.2	2.0	0.1	1.6
	L94ran	0.8	11	0.7	11	2.1	19	1.1	14	0.6	13



**Table 6.** Statistical errors of the LEG-derived fluxes in flight #5 (coupled STBL): standard deviation among subsegments (Std7), systematic and random errors according to L94 (L94sys and L94ran).

Variable		LEG5		LEG4		LEG3		LEG2		LEG1	
Height [m]		307		553		819		1079		2018	
$B$	$[10^{-4}\text{m}^2\text{s}^{-3},\%]$	1.1		0.1		8.0		-0.1		-0.5	
	Std7	2.7	243	2.8	3055	4.4	55	0.2	170	0.4	84
	L94sys	0.1	12.1	0.0	20.9	0.5	6.2	0.0	1.2	0.0	1.6
	L94ran	0.5	46	0.2	188	2.3	28	0.2	149	0.2	40
$S$	$[10^{-4}\text{m}^2\text{s}^{-3},\%]$	2.7		1.6		1.7		0.9		1.0	
	Std7	5.1	272	2.0	235	1.4	110	0.6	68	1.1	124
	L94sys	0.5	17.3	0.0	1.9	0.0	0.8	0.1	8.9	0.1	5.6
	L94ran	1.9	69	1.4	87	1.5	88	0.8	86	0.4	41
$Q_s$	$[\text{W m}^{-2},\%]$	4.0		7.2		38.0		-0.6		1.2	
	Std7	2.7	66	6.6	91	20.5	54	0.4	70	0.8	66
	L94sys	0.2	5.6	0.4	6.2	2.2	5.8	0.0	8.6	0.0	1.9
	L94ran	1.3	33	3.3	46	8.9	23	0.6	104	0.8	67
$Q_l$	$[\text{W m}^{-2},\%]$	50.4		5.0		104.6		0.1		0.0	
	Std7	22.9	45	22.6	456	77.7	74	1.0	975	0.0	75
	L94sys	2.8	5.6	0.1	2.9	5.1	4.9	NaN	NaN	0.0	4.7
	L94ran	13.7	27	13.9	281	22.9	22	8.3	7869	0.0	81

**Table 7.** Statistical errors of the LEG-derived fluxes in flight #14 (decoupled STBL): standard deviation among subsegments (Std7), systematic and random errors according to L94 (L94sys and L94ran).

Variable		LEG1		LEG2		LEG3		LEG5		LEG4	
Height [m]		143		287		448		992		2021	
<i>B</i>	$[10^{-4}\text{m}^2\text{s}^{-3},\%]$	2.7		0.3		-0.3		2.6		-0.2	
	Std7	1.5	57	0.5	185	1.7	533	0.9	36	0.2	80
	L94sys	0.0	1.7	0.0	0.1	0.1	15.4	0.1	4.4	0.0	1.2
	L94ran	0.6	24	0.5	183	0.5	138	0.9	37	0.1	53
<i>S</i>	$[10^{-4}\text{m}^2\text{s}^{-3},\%]$	0.7		2.3		1.5		1.7		0.1	
	Std7	0.9	137	0.9	67	1.3	87	1.6	125	0.1	175
	L94sys	0.0	1.3	0.0	1.5	0.0	1.8	0.0	2.6	0.0	0.3
	L94ran	0.7	94	1.2	51	1.1	70	1.4	79	4.7	4830
<i>Q<sub>s</sub></i>	$[\text{W m}^{-2},\%]$	8.9		1.6		3.6		2.5		0.4	
	Std7	3.3	37	4.1	252	2.7	75	3.8	154	0.6	177
	L94sys	0.1	0.8	0.0	0.0	0.1	4.1	0.1	5.3	0.1	24.1
	L94ran	3.3	37	14.3	884	1.6	46	1.6	63	0.1	33
<i>Q<sub>l</sub></i>	$[\text{W m}^{-2},\%]$	76.7		39.3		6.8		11.5		0.8	
	Std7	36.1	47	28.1	72	43.5	639	23.3	203	0.7	93
	L94sys	1.3	1.7	0.6	1.5	0.9	12.8	1.1	9.7	0.1	8.8
	L94ran	17.5	23	10.1	26	13.4	197	33.8	294	0.8	107

## Response to the Anonymous Referee #2

### General comments

1. The paper provides interesting insights into the stratification and the turbulent properties of coupled (CP) and decoupled (DCP) marine stratocumulus-topped boundary layers. It would be interesting to have additional CP/DCP cases to investigate whether the same pattern is also observed in other cases. Are you planning to extend the analysis to more cases? It would be in particular interesting to have more data in the stratocumulus layer.

We are grateful for the comment, which partly coincides with the first comment from the reviewer #4 (Ian Brooks). We will consider extending this analysis to other available cases, though, as usual this will depend on the available manpower. For this manuscript, we have chosen to focus on details rather than an extended data set. However, we also believe that extending similar analyses to more flights will make the results more robust.

On the other hand, the ACORES data alone might not be sufficient to provide statistically sound conclusions and we consider extending the analyzed dataset with the available data from other field experiments. In total, there were 17 research flights during the ACORES (Siebert et al., 2021, Table 5). Five of them correspond to clear-sky conditions, four to already dissipating or not yet developed stratocumulus clouds which limits the true STBL observations to 8 flights. Each flight lasted up to about 2 hours. This flight time was always disposed between sampling the cloud top structure and the boundary layer itself.

2. In Sect. 2.2, you introduce the different instruments that have been used in the study. I would like to see further discussion regarding the uncertainties of the measurements. Currently, uncertainties are not discussed and the error bars only include the variability of the data. This makes it difficult to assess the conditions inside the different sublayers in the CP and DCP case (e.g., add error bars in Table A1 and A2).

In our study, we present a great variety of turbulence parameters. We suppose it is impossible to apply one universal and rigorous approach of error treatment for such different variables. For this reason, we decided to report subsegment variability because it can be evaluated regardless of the details of a particular derivation method. On the other hand, we agree with the reviewers that the issue of uncertainties was not comprehensively addressed. In order to improve this, we complemented the manuscript with a few additional paragraphs discussing the aspects which we find the most relevant for the derived turbulence parameters.

We described the capabilities of the instruments onboard ACTOS in sec. 2.2.

The standard deviations due to uncorrelated noise for sonic measurements are  $0.02 \text{ m s}^{-1}$  for wind and  $0.02 \text{ K}$  for virtual temperature (Siebert and Muschinski, 2001). The PT100 was calibrated prior to the campaign in a thermostated water tank using the Greisinger GMH 3750 reference thermometer which provides accuracy better than  $0.05 \text{ K}$ . The UFT was calibrated for each flight separately against the PT100. For the UFT records, the standard deviation due to uncorrelated noise is  $4 \text{ mK}$  (Siebert et al., 2003). The hygrometer

provides  $q_v$  with a noise floor of about  $0.005 \text{ g kg}^{-1}$ . This instrument was verified to agree well with a few hygrometers of different types and operate satisfactorily on the helicopter-towed system Helipod by Lampert et al. (2018). The PVM-100A measures  $q_l$  with the accuracy of 5 % and its noise floor was estimated by Siebert et al. (2003) for about  $0.001 \text{ g kg}^{-1}$ . The exact sensitivity depends to some extent on droplet size distribution, see Wendisch et al. (2002) for details. For a more general discussion of the instrumentation on the ACTOS platform see Siebert et al. (2006a).

We discussed the sampling errors (systematic and random) for turbulent moments (variances, TKE,  $\langle w'^3 \rangle$ ) estimated according to Lenschow et al. (1993, 1994) in sec. 4.1. The detailed procedure with all the specific values is delineated in our response to the Anonymous Reviewer #1.

The accuracy of the results is severely limited by the length of the LEGs. Based on the methods of Lenschow et al. (1994), in the boundary layer the variances are subject to the systematic sampling error of about 5 % and the random sampling error of about 20 %. In the case of  $\langle w'^3 \rangle$ , those errors are accordingly larger (order of 10 % and 100 %, respectively, unless  $\langle w'^3 \rangle$  is not very close to zero). Importantly, in the plots we provide the variability among subsegments which was found to be of the same order as the total sampling error, in most cases larger than it.

Similarly, we discussed the sampling errors for turbulent fluxes in sec. 4.2. Again, please see the response given to the Anonymous Reviewer #1 to find the tables presenting all the individual errors.

Similarly to variances, the accuracy of the fluxes obtained with the method of eddy correlation is limited by the length of the LEGs. In the boundary layer, the systematic sampling error was estimated for about 5-10 % while the random sampling error for about 50 % (Lenschow et al., 1994), unless the flux does not vanish. The subsegment variability (marked with errorbars in the plots) is in most cases larger than the total sampling error.

We estimated the uncertainties of the derived dissipation rates and SFC/PSD slopes due to random errors in sec. 4.3.3. In addition, we proposed alternative methods of a rather qualitative assessment of the reliability of the results.

In order to roughly estimate the uncertainties of the results, we used the random errors of the fitted parameters (computed with a standard method from least-squares fit residuals). The random error of ‘instantaneous’ (calculated in 2 s windows and serving for the derivation of the profiles) dissipation rate equals  $\sim 50 \%$  in the boundary layer and  $\sim 150 \%$  in the FT. The error of the LEG-derived  $\epsilon$  is  $\sim 30 \%$  for longitudinal component and  $\sim 15 \%$  for vertical component in the boundary layer while  $\sim 150 \%$  for both components in the FT. The random error of the fitted slopes is  $\sim 0.04$  for  $s$  and  $\sim 0.16$  for  $p$  corresponding to the ‘instantaneous’ estimations while  $\sim 0.02$  in the case of both LEG-derived slopes. Notwithstanding, the given values represent the uncertainties due to the random errors of the fit only. The reliability of the derived dissipation rates can be

also assessed by comparing the results of the two derivation methods, by comparing the fitted SFC and PSD slopes with their theoretical values or using the deviation of the computed correlation coefficients from unity.

The uncertainties of further quantities derived from dissipation rate can be estimated by the method of error propagation. Additionally, we referred to the previous works to argue that the analysis of spectral anisotropy (sec. 4.4 and 5.4) is justified taking into account the quality of our data. Our data is sufficient for the analysis of the inertial range anisotropy as Siebert and Muschinski (2001) demonstrated that the spectra of velocity fluctuations measured with an earlier version of our ultrasonic anemometer-thermometer in a considerably turbulent environment follow closely the expected  $5/3$  power law, a flattening is observed only at frequencies larger than 30 Hz and the ratio of the transverse and longitudinal spectra equals  $4/3$ , as predicted for isotropic turbulence.

3. The paper contains many abbreviations (e.g., for the different sublayers). I understand that it makes sense to introduce these abbreviations, as they are frequently used in the paper. However, for the readers that are not familiar with these abbreviations, it can be hard to remember the definition of the different acronyms and to follow the text. Please check if all the abbreviations are necessary. For example, “ENA” and “CTEI” are only used 2-3 times and could be removed. Furthermore, I would suggest including the abbreviations of the different sublayers in the figures, in order to make it easier for the reader to identify them (see specific comments).

Following the suggestion of this and other reviewers we reduced the number of acronyms by replacing them with the corresponding expanded expressions, in particular those which were not used frequently in the text. This group includes: SC, BL, ENA, TAS, CTEI, J11, WB04, YA00, CP, DCP. The last two were shortened to C and D, respectively, and only kept in sec. 6 to order the list of conclusions. We prefer to keep the acronyms of the following types:

- denoting the sublayers of the atmosphere: STBL, SML, TSL, SBL, SCL, EIL, FT, because they are used very frequently in the text as well as in tables and figures,
- denoting our flight segments: PROF, LEG, for the same reason,
- commonly used abbreviations: TKE, LCL, SFC, PSD, because we expect them to be familiar to the readers,
- names of instruments or platforms: ACTOS, SMART-HELIOS, MODIS, GPS, for the same reason.

Moreover, we added the expanded names of the sublayers to the headings of Tables A1 and A2.

The abbreviations denoting different sublayers were added to Figs. 5, 6, 9, 10, 11, 12, 13, 14, 15, 16, 19, 20 as suggested.

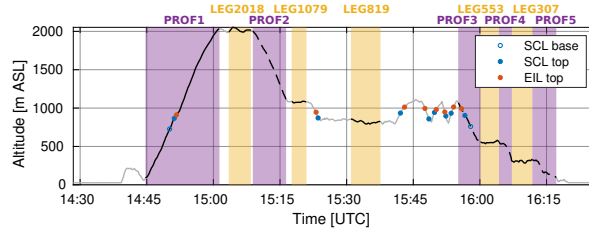
### **Specific comments**

4. Page 5, caption Fig. 1 and caption Fig.3: Please add date and time of satellite image.

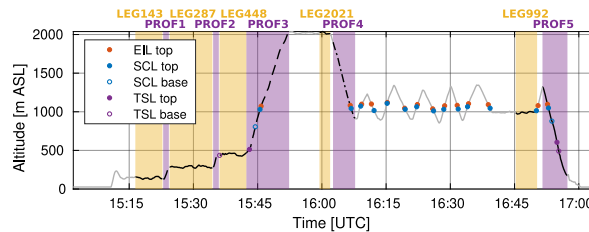
The captions were corrected as suggested. Fig. 1. shows the imagery acquired on 8 July 2017 at 15:45 UTC, Fig. 3. on 18 July 2017 at 14:43 UTC.

5. Page 5, Fig. 2 and Fig. 4: In Fig. 2 and Fig. 4 you show the time series of the ACTOS altitude. I think it would be beneficial to include more information regarding the cloud/BL structure. E.g., At what altitude is the cloud top/cloud base? You could indicated the different sublayers on the right side of the plot. Furthermore, you often refer to the different profiles (PROFs 1-5) and legs (LEGs 1-5) throughout the paper. You could consider adding the labels of the profiles and legs on top of the plot. In addition, the line style of the profiles is not evident in the figure due to the low contrast between the black line in the background and the black dotted line. I would suggest to remove the black line in the background or to change the color to get a better contrast.

The figures were modified according to the suggestions. The labels denoting PROFs and LEGs were added at the top. The ordering of LEGs was changes into LEGX where X stands for mean altitude (m a.s.l.), following the request of another reviewer. The grey line illustrating altitude profile for the whole flight was plotted only outside the colored segments to improve the visibility of the black line used within the segments. Instead of sublayer labels, the individual penetrations (determined manually) of the EIL top, SCL top (=EIL base), SCL base (=SBL top), TSL top (=SBL bottom) and TSL base were indicated in the altitude profile with additional symbols.



**Figure 2 corrected.** ACTOS altitude in flight #5 with marked selected profiles and horizontal legs. PROFs are ordered chronologically, LEGs are ordered according to their altitude. Line styles of the PROFs are consistent with the figures in following sections Altitude ranges corresponding to PROF2-PROF5 of this flight do not overlap and are all marked with dotted lines. Dots indicate the penetrations of the boundaries of the specific sublayers described in sec. 3.



**Figure 4 corrected.** As in Fig. 2 but for flight #14. Line styles of the PROFs are consistent with the figures in following sections. PROF1-PROF3 are all marked with dotted lines because their altitude ranges do not overlap.

6. Page 6, equation 1: You defined ‘ql’ as the liquid water content on page 4, line 103. The liquid water content is usually defined as mass of liquid water per volume of air (i.e.  $g\ m^{-3}$ ). However, in equation 1 the liquid water mixing ratio

(i.e. mass of liquid water per unit mass of air) should be used and not the liquid water content (see Betts 1973 or the following link: [https://glossary.ametsoc.org/wiki/Liquid\\_water\\_potential\\_temperature](https://glossary.ametsoc.org/wiki/Liquid_water_potential_temperature)). Please review your definition of ‘ql’ in the manuscript.

In our calculations and throughout the manuscript  $q_l$  denotes liquid water mass fraction, i.e. mass of liquid water in a unit mass of moist liquid-laden air. Its units are  $\text{g kg}^{-1}$ . It is consistent with Eq. (14) of Betts (1973) and with  $q_t = q_v + q_l$  being a conservative quantity. Such definition is related to liquid water content (mass of liquid water per unit volume of air)  $\rho_l$  and to liquid water mixing ratio (mass of liquid water per unit mass of dry air)  $r_l$  as the following:

$$q_l = \frac{\rho_l}{\rho_d + \rho_v + \rho_l} = \frac{r_l}{1 + r_v + r_l}, \quad r_l = \frac{\rho_l}{\rho_d} \quad (1)$$

where  $\rho_d$  is density of dry air,  $\rho_v$  is density of water vapor and  $r_v$  is water vapor mixing ratio. We corrected the erroneous definition in the text.

... liquid water mass fraction  $q_l$  determined with the Particle Volume Meter ...

7. Page 7, line 150: According to J11, ‘qt’ should be the total water mixing ratio, which is defined by the sum of the liquid water mixing ratio and the water vapor mixing ratio (see also comment 6). Please review your definition of ‘qt’ in the manuscript.

In our calculations and throughout the manuscript  $q_t$  denotes total water mass fraction, i.e. the total mass of liquid water and water vapor per unit mass of moist liquid-laden air (see also the answer to comment 6 above):

$$q_t = q_v + q_l = \frac{\rho_v + \rho_l}{\rho_d + \rho_v + \rho_l} = \frac{r_t}{1 + r_t}, \quad r_t = r_v + r_l, \quad r_v = \frac{\rho_v}{\rho_d} \quad (2)$$

where  $q_v$  is water vapor mass fraction (specific humidity),  $q_l$  is liquid water mass fraction,  $\rho_d$  is density of dry air,  $\rho_v$  is density of water vapor,  $\rho_l$  is liquid water content.  $r_v$  is water vapor mixing ratio,  $r_l$  is liquid water mixing ratio and  $r_t$  is total water mixing ratio. Insofar, we indeed used slightly different criterion than J11 who applied total water mixing ratio  $r_t$  instead of our total water mass fraction  $q_t$ . This difference do not affect the conclusions reached with the use of the criterion because approximately  $q_t \approx r_t$ . This controversy was briefly explained in the text.

The first criterion of Jones et al. (2011) involves the differences of  $\theta_l$  and total water mixing ratio between the uppermost and the lowermost quarters of the boundary layer (instead of the latter quantity, we used our total water mass fraction  $q_t = q_l + q_v$  which does not influence the conclusions because those two measures are approximately equal).

In contrast to the criterion of Jones et al. (2011), in the one of Yin and Albrecht (2000) we did use the water vapor mixing ratio  $r_v$  following those authors literally because there is derivative of this quantity involved (i.e. in general, under some conditions small discrepancies might affect the result).

8. Page 9, Fig. 5 and Fig. 6: As mentioned already in the general comment section, it is hard to remember the abbreviations of the different sublayers. In order to make it easier for the reader to follow and identify the different sublayers, I would suggest adding the abbreviations of the sublayers (color shaded areas) on the right side of the subplots (for all figures of this type; i.e. Fig. 5, 6, 9-16, 19-20). Furthermore, I would plot the lines on top of the shaded area to avoid any change in the line color (for example for LCL, qv).

The acronyms denoting different sublayers were added to Figs. 5, 6, 9, 10, 11, 12, 13, 14, 15, 16, 19, 20 as suggested. Moreover, their full names were given in the tables in the appendix. We appreciate recognizing the issue with colors while plotting the shaded areas. We changed the order of drawing in our routine as suggested.

9. Page 9, line 207: So are both the upper and the lower BL portion internally mixed? If yes, you could change the structure of the sentence as follows: “This suggests that both the upper and lower BL portion are internally mixed.”

Yes, they are. We corrected the sentence as suggested.

10. Page 14, line 113: You applied a moving window of 2 s to the profiles. How was the moving window of 2 s determined? Did you conduct sensitivity tests with different time windows?

In a few previous studies which utilized the same type of data, the window of 1 s was proven to operate satisfactorily while deriving the instantaneous dissipation rate (e.g. Siebert et al., 2006b; Katzwinkel et al., 2012). The choice of such window length by Siebert et al. (2006b) followed from their own sensitivity tests and the works of Muschinski et al. (2004); Frehlich et al. (2004). Because we determine not only the dissipation rate but also the slope of the SFC or the PSD in the inertial range, we decided to increase the window to 2 s so that the linear fit covers the considerable portion of the inertial range (0.4-40 m) and the sufficient number of logarithmically equidistant resampled points (eight per decade, see sec. 4.3 of the manuscript). We did not conduct additional strict sensitivity tests within the present study. The appropriate explanatory comment was added to the text.

Our approach follows earlier studies which determined the instantaneous dissipation rate utilizing the same type of data as ours (Siebert et al., 2006b; Katzwinkel et al., 2012). Siebert et al. (2006b) have chosen the window of 1 s based on their sensitivity tests and the arguments provided by Frehlich et al. (2004) and Muschinski et al. (2004). Because we derive not only  $\epsilon$  but also the slopes and correlations, we increased the window to 2 s so that the linear fit covers considerable portion of the inertial range and the sufficient number of logarithmically equidistant resampled points (see sec. 4.3.1).

11. Page 20, Fig.13: Why is there such a large discrepancy between some of the PROFs and LEGs properties (e.g.,  $s_u$ ,  $R_u$ ,  $R_w$ ) in the FTL?

First, the free troposphere is not expected to be turbulent. Under such conditions, the assumptions of Kolmogorov theory exploited in both the methods of dissipation rate derivation are far from being fulfilled. Structure functions and power spectra are not guaranteed to follow any specific scaling. The inertial range cannot be defined.



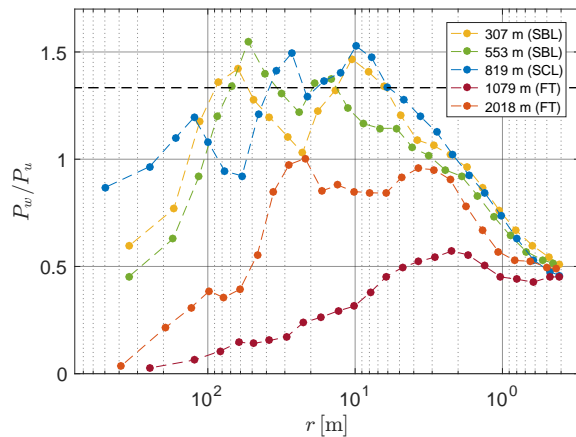
Second, even in the STBL the results on small-scale turbulence, including  $\epsilon$ ,  $s$  and  $p$ , should not be compared between PROFs and LEGs in a straightforward way. They are representative for small and large fluid volumes, respectively. Note that the climb rate of the helicopter is much higher than of a typical research aircraft (c.f. Siebert et al., 2021, sidebar "Profiling with aircraft and helicopter"). Also, horizontal segments may cover various air volumes differing in turbulence intensity and its properties, e.g. dissipation rate or inertial range scaling. According to the refined Kolmogorov hypothesis (Kolmogorov, 1962), due to turbulence intermittency  $\epsilon$  distribution depends on the scale on which it is evaluated. This dependence inside clouds was investigated experimentally by Siebert et al. (2010).

We added a comment about this issue in sec. 5.3.

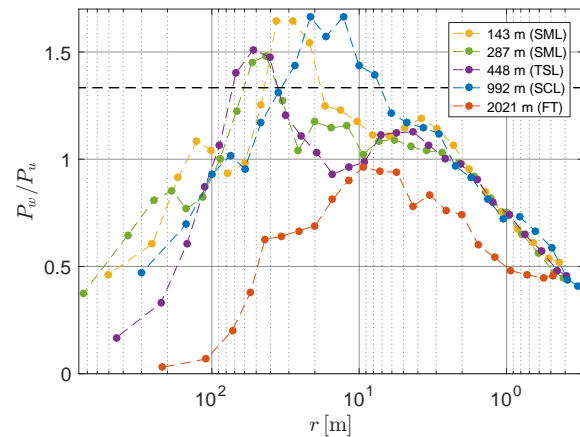
In contrast to the PROFs, the LEG-derived exponents stay mostly close to  $2/3$  or  $-5/3$ , accordingly, while the correlations are close to one. The observed discrepancy might result from the combination of horizontal inhomogeneity and intermittency of turbulence. PROF-derived and LEG-derived parameters should not be directly compared because they represent small and large fluid volumes, respectively. Unfortunately, none of the horizontal segments was performed in the SBL.

12. Page 24, Fig. 17 and Fig. 18: I would use the same scale on the y-axis for Fig. 17 and Fig. 18 for better comparison between the coupled and decoupled case. Furthermore, I would suggest adding the sublayer in brackets next to the altitude.

The figures were modified according to the suggestions.



**Figure 17 corrected.** Spectral anisotropy ratio in the coupled STBL (flight #5). The horizontal dotted line denotes the  $4/3$  level expected for isotropy in inertial range.



**Figure 18 corrected.** As in Fig. 17 but for the decoupled STBL (flight #14).

13. Page 25, line 506: "Lengthscales" should be changed to "Length scales" throughout the paper.

The text was corrected accordingly.

14. Page 25, line 512 and line 524: One of the “ $\lambda_u$ ” in the ratio should be replaced by “ $\lambda_w$ ”.

Obviously. We are sorry for the typo.

15. Page 32, line 669: Change “imortant” to “important”

Corrected.

16. Page 32, line 670: Change “proprties” to “properties”

Corrected.

### **Response to the Anonymous Referee #3**

This may seem a minor point... The use of acronyms and abbreviations in the paper... I have no quarrel with use of commonly accepted acronyms and abbreviations like CCN, TKE, CAPE, etc... Using ACTOS instead of Airborne Cloud Turbulence Observations System every time is preferable. However, this paper has gone too far, in my opinion, with acronyms and abbreviations.

Abbreviating “coupled” by CP, for example, saves 5 letters, but introduces the additional effort required to recall that CP means “coupled” in this context.

I lost the thread of many arguments through the paper because I kept having to go back and find what CP or SCL or TSL meant. I know it makes the paper a little bit longer, but it would be much, much more readable if fewer abbreviations were used.

Following the suggestion of this and other reviewers we reduced the number of acronyms by replacing them with the corresponding expanded expressions, in particular those which were not used frequently in the text. This group includes: SC, BL, ENA, TAS, CTEI, J11, WB04, YA00, CP, DCP. The last two were shortened to C and D, respectively, and only kept in sec. 6 to order the list of conclusions. We prefer to keep the acronyms of the following types:

- denoting the sublayers of the atmosphere: STBL, SML, TSL, SBL, SCL, EIL, FT, because they are used very frequently in the text as well as in the tables and figures,
- denoting the flight segments: PROF, LEG, for the same reason,
- commonly used abbreviations: TKE, LCL, SFC, PSD, because we expect them to be familiar to the readers,
- names of instruments or platforms: ACTOS, SMART-HELIOS, MODIS, GPS, for the same reason.

Moreover, we added the expanded names of the sublayers to the headings of Tables A1 and A2.

## Response to Ian Brooks

The results are, for the most part, routine – such boundary layers are well studied (even if our understanding of all the interacting processes is incomplete), and most of the results are in broad agreement with previous studies (as noted in the conclusions). They remain, however, a useful contribution to the field, and do include some unique results – those of very small-scale turbulent properties: profiles of dissipation rate, and isotropy.

We agree with the general assessment that part of our analysis confirms known findings. From our point of view, these analyses are nevertheless important at this point in order to be able to correctly classify and evaluate the observations of small-scale turbulence. This makes the manuscript a bit longer, but we think - like another reviewer - that this is justified in this case. We believe that a reader should be able to navigate through the text using the section and subsection titles, e.g. skip some of the analyses without losing the thread and find the information which is relevant for him.

There is a limit to how much can be gained from analysis of individual case studies. I would encourage the authors to consider expanding their analysis in future to include all the flights from this campaign (many more than the two used here) to produce a more general synthesis of turbulent behaviour for the coupled and decoupled boundary layers.

This is definitely a suggestion that will be considered for the future. Here, we had to find a compromise between detail and scope, so we first decided to focus on two case studies with a lot of detailed analysis. For the future, we will explore individual aspects with more data to make the results more statistically significant.

On the other hand, the ACORES data alone might not be sufficient to provide statistically sound conclusions and we consider extending the analyzed dataset with the available data from other field experiments. In total, there were 17 research flights during the ACORES (Siebert et al., 2021, Table 5). Five of them correspond to clear-sky conditions, four to already dissipating or not yet developed stratocumulus clouds which limits the true STBL observations to 8 flights. Each flight lasted up to about 2 hours. This flight time was always disposed between sampling the cloud top structure and the boundary layer itself.

## Specific comments

1. The overall structure of the manuscript follows the conventional pattern of background / methods / results / conclusions. This is fine, but I found that the sheer number of different variables being defined resulted in a very long methods sections, where it wasn't always clear what the real utility of a particular parameter was. By the time the reader (or this reader anyway) gets to the relevant results, they've forgotten what all the different symbols and parameters are. It might be worth considering modifying the structure to mix parameter definitions and results – defining/explaining particular quantities immediately prior to presenting the results on them. This is very much a decision to be made on personal preference regarding the readability, I'm sure another reviewer would argue against doing this.

We did consider the suggested structure of the manuscript. Actually, our first internal draft followed exactly this approach. However, we came to the conclusion that the multiple explanations of the applied methods disturb a consistent

presentation of the results. Another argument in favor of a classical structure is that the reader knows where to expect which content. We are aware that our manuscript is rather long and with its structure we intended to enable readers to easily find the information which is the most relevant for them. Some might be interested in the results only, some in the very details of our methods.

2. On a related note, there are a LOT of acronyms defined here, not all of them are used very often (eg ‘CB’ is only used 6 times after being defined. . . not worth the space saving traded off against having to go back and find out what it means’. I found it easy to confuse many of these because of minor inconsistencies in how the layer names mapped to acronyms– I kept reading ‘SCL’ as ‘sub-cloud layer’ instead of ‘stratocumulus layer’, whereas ‘SBL’ (sub-cloud layer) I wanted to read as ‘stable boundary layer’ . . . which is a common usage, but irrelevant here.

Following the suggestion of this and other reviewers we reduced the number of acronyms by replacing them with the corresponding expanded expressions, in particular those which were not used frequently in the text. This group includes: SC, BL, ENA, TAS, CTEI, J11, WB04, YA00, CP, DCP. The last two were shortened to C and D, respectively, and only kept in sec. 6 to order the list of conclusions. We prefer to keep the acronyms of the following types:

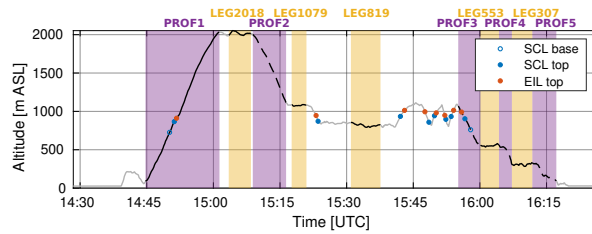
- denoting the sublayers of the atmosphere: STBL, SML, TSL, SBL, SCL, EIL, FT, because they are used very frequently in the text as well as in tables and figures,
- denoting our flight segments: PROF, LEG, for the same reason,
- commonly used abbreviations: TKE, LCL, SFC, PSD, because we expect them to be familiar to the readers,
- names of instruments or platforms: ACTOS, SMART-HELIOS, MODIS, GPS, for the same reason.

Moreover, we added the expanded names of the sublayers to the headings of Tables A1 and A2.

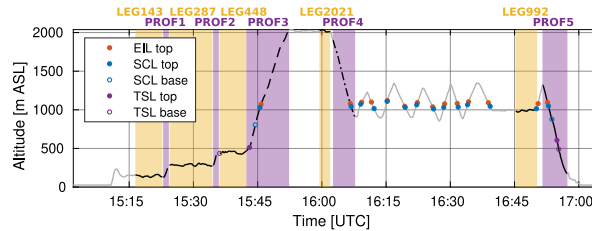
3. Figure 2 and 4 – it might be useful to indicate cloud base and top on the figures so the reader can immediately see how the flight legs relate to cloud level. The line style for different sections of the flight track are consistent with those used on the later profile plots - this is clear for fig 4 (flight 14) where the profile plots show 3 distinct profiles; but less so on fig 2 (flight 5) where there are only 2 line types. It appears that in the profile plots the dashed line, which looks like a single deep profile, is actually a composite of several profile sections separated in time, and spanning different altitude ranges. This is fine, but should be made explicit since it has a bearing on variability of the data.

The figures were modified. The individual penetrations (determined manually based on  $\theta_v$ ,  $q_v$  and  $q_l$  records) of the EIL top, SCL top (=EIL base), SCL base (=SBL top), TSL top (=SBL bottom) and TSL base were indicated in the altitude profile with additional symbols. The labels denoting PROFs and LEGs were added at the top. The grey line illustrating altitude profile for the whole flight was plotted only outside the colored segments to improve the visibility of the black line used within the segments.

Indeed, the same line style was used for several PROFs which do not overlap in their altitude ranges. We agree this might have been confusing. Therefore, additional short explanation was added to the text and the captions.



**Figure 2 corrected.** ACTOS altitude in flight #5 with marked selected profiles and horizontal legs. PROFs are ordered chronologically, LEGs are ordered according to their altitude. Line styles of the PROFs are consistent with the figures in following sections. Altitude ranges corresponding to PROF2-PROF5 of this flight do not overlap and are all marked with dotted lines. Dots indicate the penetrations of the boundaries of the specific sublayers described in sec. 3.



**Figure 4 corrected.** As in Fig. 2 but for flight #14. Line styles of the PROFs are consistent with the figures in following sections. PROF1-PROF3 are all marked with dotted lines because their altitude ranges do not overlap.

4. At various points in the discussion of results, specifically the plots of profiles and leg-averaged values, reference is made to a particular flight leg ‘LEG2’, ‘LEG3’ etc. I found this unhelpful, since I couldn’t immediately identify which leg was which on the plots. . . what altitude was it? It would be more useful to simply refer to the altitude of the leg.

The legs can be identified by referring back to figures 2 and 4, but (a) that requires the reader to go searching back for the relevant figure, and (b) there is a potential cause for confusion, because the leg numbering (assuming it is chronological. . . this is never explicitly stated) appears to be inconsistent when referred to the profiles, since for flight 5 the legs start high and work down, and on flight 14 start low and work up (and then down again for final leg). All we really need to know in the discussion is the altitude, the leg number is a distraction’

The numbering of LEGs and PROFs in our manuscript was chronological which was stated in line 111, page 4. We agree that such a convention may be confusing for the reader. Therefore, the ordering of LEGs was changed into LEGX where X stands for mean altitude (m a.s.l.). For PROFs, we kept the chronological numbering. We improved the clarity of the relevant explanation in sec. 2.3. In addition, the labels denoting PROFs and LEGs were added at the top of Figs. 2 and 4.

Segments of two types were selected from the measurement records: profiles (PROFs) and horizontal legs (LEGs). For convenience, for each flight PROFs are ordered chronologically according to their time of

execution and referred to as PROF1-PROF5 while LEGs are ordered according to their mean altitude (m above sea level).

5. Line 169: ‘Negative values suggest instability...’ – for clarity it would be useful to explicitly state the variables involved here ‘Negative values of  $Dq_l$  suggest...’

Corrected accordingly. ‘Negative values of  $\Delta\theta_l$  and  $\Delta z$  suggest instability ...’

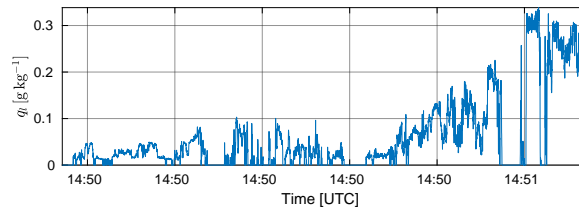
6. Line 171 ‘The parameter of YA00...’ – again, be clear and name the parameter, not (just) the paper where it was first defined... make it easy on the reader.

Corrected accordingly. ‘The parameter  $\mu$  is plotted ...’

7. Line 186: ‘probably there were some clearings...’ – while the effects of such clear air regions will get averaged out by the vertical binning/averaging/smoothing applied to generate the profiles, it ought to be possible to identify if they actually occur from the raw, high rate data, and not have to rely on a vague statement of ‘probably’.

We verified there were indeed some cloud clearings indicated by our high rate data of  $q_l$ . See the plot below. The text was updated accordingly.

There were cloud clearings penetrated as ACTOS moved along the slanted path, visible in the high rate records of  $q_l$  (not shown here).



**Figure.** Cloud penetration during PROF1 of flight #5.

8. Line 202-203: ‘Suitable normalisation...’ – Purely my preference, but I’d cut this line. I don’t think it adds anything useful unless you go into detail about the normalisation & averaging referred to.

We removed the sentence. By suitable normalization we meant the method of Ghate et al. (2015). They identified STBL sublayers in each sounding, normalized the height so that each sublayer has the depth of 1 and then averaged the relevant properties at the normalized heights. This method of profile averaging preserves the sublayer structure despite the depths of the sublayers may vary between the individual soundings.

9. Line 232: what are the instrument issues that resulted in problems with the lateral wind components? It’s not essential to document this, but, depending on the cause, might be useful for other researchers trying to make similar measurements.

We observed artificial jumps of the amplitude  $0.1 - 1 \text{ m s}^{-1}$  in the records of the lateral horizontal component which seems to appear for true air speeds above about  $12 \text{ m s}^{-1}$  or so. There were virtually no signs of such behavior in the records of the other two velocity components. As far as we know, the issue is specific for that ultrasonic anemometer model. Wind tunnel investigations suggest a problem with the transformation between the axis aligned coordinate system into an orthogonal system. The artifacts were almost not visible along the transducer pairs. However, you have to make a decision which system you want to select for data storage before the flight - we stored in an orthogonal system. Nonetheless, we are not absolutely sure about the reason. Therefore, we prefer not to share the speculations in the published paper until a proper investigation is completed. We added short information to the text:

The lateral channel of the ultrasonic anemometer was affected by a substantial level of artificial fluctuations (up to  $1 \text{ m s}^{-1}$  in amplitude) due to instrumental issues. The origin of this problem is under investigation. It seems to appear for true air speed above about  $12 \text{ m s}^{-1}$  which makes it relevant for most of the flight time.

10. Line 294 and 307: both reference a ‘lateral component’ when the parameter referred to is derived from vertical velocity. Yes,  $w$  is ‘lateral’ with respect to the mean wind vector, but it might be clearer here to be explicit and refer to the ‘vertical component’, not least because you have previously noted problems with the ‘lateral’ velocity measurements, where lateral refers to the horizontal cross-wind component, and so is a potential source of confusion.

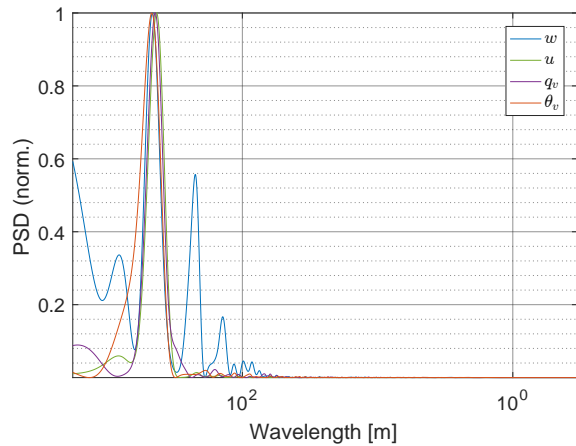
We are grateful for pointing out this inconsistency. Indeed, the reason for the confusion was that we used the word ‘lateral’ to name two different aspects: (1) the component  $v$  and (2) the orientation with respect to the mean wind vector which is relevant for turbulence theory and the choice of the constant  $C$  (then both  $v$  and  $w$  are considered lateral in contrast to longitudinal  $u$ ). We corrected the description according to the suggestion by sticking to the meaning (1).

11. Line 374-377: The unexpectedly high variances above cloud are presumed to be artefacts resulting from the presence of gravity waves. While I agree that is quite likely, it should be possible to demonstrate it. Coherence/phase/amplitude plots of the correlation between vertical velocity and the other variables should show a clear scale of waves. Power spectra or ogive plots of variances/covariances should also show that most of the variance/covariance results from a narrow range of wavelengths that can be related to gravity waves.

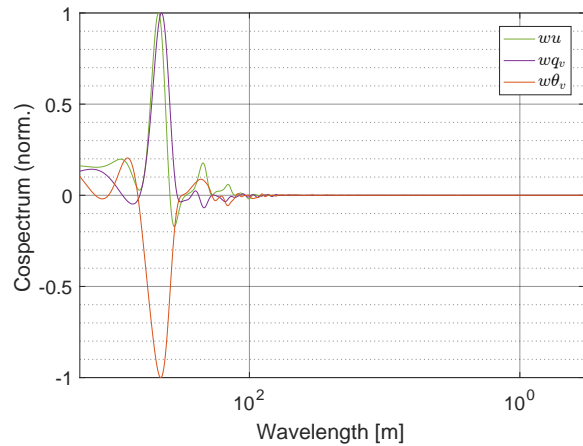
We prepared a brief analysis of the fluctuations recorded in the first half of LEG1079 for which we noticed some quasi-regular oscillations. The figures below present power spectra of  $w$ ,  $u$ ,  $q_v$ ,  $\theta_v$  and cospectra of  $wu$ ,  $wq_v$ ,  $w\theta_v$ . We applied Welch scheme implemented in MATLAB functions `pwelch` and `cpsd`.

All the power spectra exhibit a pronounced peak at the wavelength of about 450 m. Hence, most of the variance can be attributed to such oscillations. The same can be observed in the cospectra. Thus, most of the covariance can be attributed to those range of wavelengths. We added a short comment justifying our speculations to the manuscript.

Estimated values of the TKE are also large in the FT above the temperature inversion. This is rather an artifact due to the presence of gravity waves favored under stable conditions (the power spectra of  $w$ ,  $u$ ,  $q_v$ ,  $\theta_v$



**Figure.** Power spectrum density of the first half of LEG1079 normalized by its maximum value (linear scale).



**Figure.** Cospectrum for the correlations in the first half of LEG1079 normalized by its maximum absolute value.

and the cospectra of  $wu$ ,  $wq_v$  and  $w\theta_v$  indicate the dominant contribution of the wavelength of about 450 m). Recall that LEG1079 was flown very close to the EIL and the cloud top which often features undulated interface.

12. Line 390: The statement regarding T and q as being passive tracers with no significant sources at the transition layer is... arguable. There is no real 'source', but for the SML, the gradient across decoupling transition layer acts as a source/sink term, entrainment mixing brings drier/warmer air down to top of SML (local effective source/sink). There must be some mixing to give high T/Q variances here.

Then... 'The TSL features the gradient of  $qv$  (c.f. Fig. 6) which might explain increased local fluctuations.' – what other source of increased fluctuations could there be here?

This is a misunderstanding due to the unclear formulation of our point. We just do not consider gradient production (Term IV of the variance budget equations in the formulation of Stull (1988), his Eqs. (4.3.2) and (4.3.3)), as 'sources'. By 'sources' we meant the processes of the type described by Term VIII in Stull's Eq. (4.3.3), e.g. radiative cooling. Obviously, gradient production is present in our case. The sentence was rewritten to clarify this issue:

*T* and  $q_v$  can be considered passive scalars which undergo mixing. The increased variances are caused by gradient production (Term IV in the variance budget equations in the formulation of Stull (1988), his Eqs. (4.3.2) and (4.3.3)) rather than by any diabatic sources.

13. Line 420: You 'speculate that the drivers of convection, i.e. radiative and evaporative cooling, are not efficient in this situation'. What is different about 'this situation' that either of these processes should be different? You can evaluate the



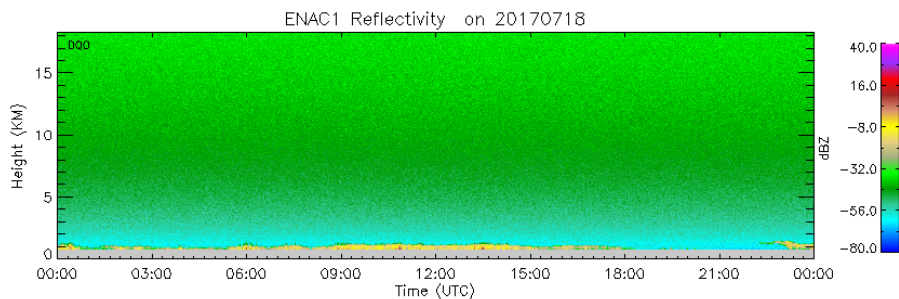
evaporative cooling and CTEI parameter. . . is this weaker than for the other case? Certainly the latent and sensible heat fluxes are much smaller in cloud here than for flight 5.

Radiative cooling is more difficult to assess without direct measurements of the radiative fluxes, but there may be clues available. You mention the availability of the ARM remote sensing data. . . does that show a higher cloud deck that might reduce the radiative cooling from cloud top? This case does have a slightly thicker cloud and so higher LWC at cloud top. . . this will slightly modify (sharpen) the LW cooling and SW heating profiles, and maybe shift the relative positions of their peaks in the vertical, changing the balance of heating/cooling.

Our speculative comment resulted from the observation of relatively small  $Q_s$ ,  $Q_l$  and  $B$  in the cloud (LEG992). This LEG was performed below the cloud top but not exactly at the interface or in the EIL, so the fluxes do not represent the entrainment of warm and dry air from the FT but rather parcels which were cooled in the cloud top region and descend through the cloud (Gerber et al., 2016).

Regarding evaporative cooling, the CTEI parameter  $\kappa$  (its estimation was given in sec. 3.2) is indeed smaller for the decoupled STBL (0.34) than for the coupled (0.71), yet exceeds the critical value for buoyancy reversal in both cases. This is consistent with the claim of less efficient evaporative cooling in our decoupled stratocumulus.

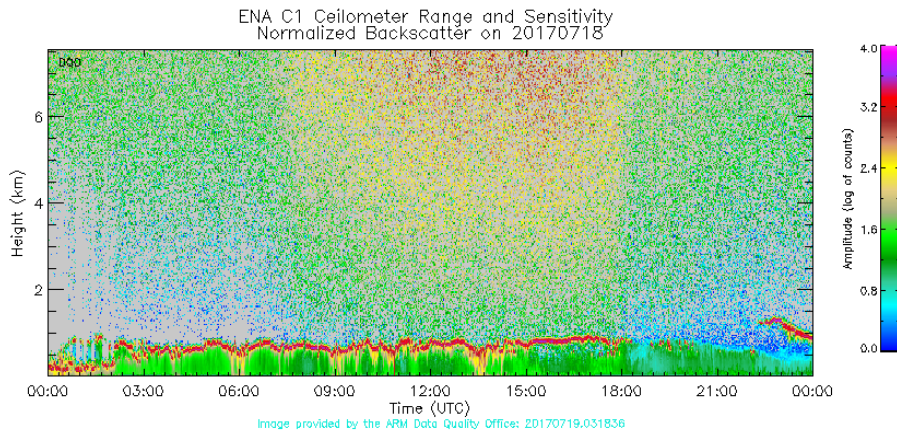
Regarding radiative cooling, there is evidence that there was no overlying cloud layer during flight #14. No additional clouds were reported by the scientists onboard the helicopter. There are also no overlying clouds visible in the measurements performed by the Ka-band cloud radar and by the ceilometer at ARM ENA site (see the figures below). Moreover, in the substantial region around the operation area, the satellite products derived from MODIS onboard Aqua (NASA Worldview portal) indicate cloud top temperature in the class of 285-290 K and cloud top height in the class of 800-1600 m, both consistent with our observations of stratocumulus top.



**Figure.** ARM ENA Ka-band Zenith Radar reflectivity. Figure downloaded from ARM Plot Browser (<https://plot.dmf.arm.gov/plotbrowser/>).

Radiative fluxes were measured in the course of the ACORES campaign by the radiometers onboard ACTOS and SMART-HELIOS. However, the data require validation and careful interpretation (e.g. related to the platform inclination and orientation changing during flight maneuvers). This is subject of ongoing work performed by the Atmospheric Radiation research group at the University of Leipzig.

Following the points raised by the reviewer, we reformulated the argumentation in the manuscript:



**Figure.** ARM ENA Ceilometer normalized backscatter coefficient. Figure downloaded from ARM Plot Browser (<https://plot.dmf.arm.gov/plotbrowser/>).

Both sensible and latent heat fluxes observed in the cloud (LEG992) are small, in contrast to the coupled case. Together with rather moderate  $B$  in the cloud this suggests that the drivers of convection, i.e. radiative and evaporative cooling, are not as efficient in this situation which might have been one of the reasons why decoupling occurred. Cloud top entrainment instability parameter  $\kappa$  (sec. 3.2) is indeed smaller in the decoupled cloud in comparison to the coupled one which implies less efficient evaporative cooling. However, the comparison of radiative cooling effects between the cases requires further investigation.

14. Line 422: ‘moisture delivery from the ocean surface to the cloud might be more difficult in the decoupled STBL’ – yes, it ought to be much more difficult.

We changed ‘might’ into ‘ought to’.

15. Line 458: is the departure of measurements from theoretical expectations for homogeneity, isotropy and stationarity here a result of evaluating them from slant profiles? You note the horizontal legs are in much better agreement with theory, suggesting the profile results are not truly representative.

The results on small-scale turbulence, including  $\epsilon$ ,  $s$  and  $p$ , should not be compared between PROFs and LEGs in a straightforward way. They are representative for small and large fluid volumes, respectively. According to the refined Kolmogorov hypothesis (Kolmogorov, 1962), due to turbulence intermittency  $\epsilon$  distribution depends on the scale on which it is evaluated. This dependence inside clouds was investigated experimentally by Siebert et al. (2010).

In our opinion, the observed discrepancy between PROF-derived and LEG-derived parameters stems from the combination of horizontal inhomogeneity and intermittency of turbulence. In fact, horizontal segments may cover various air volumes differing in turbulence intensity and its properties, e.g. dissipation rate or inertial range scaling. In the region of decaying turbulence, which is likely in the SCL and the SBL of the decoupled boundary layer, there can be even laminar

patches. Under such conditions, the scaling of a power spectrum or structure function is dominated by the most intensive portions. In contrast, PROFs are considered to capture local properties. Note that the climb rate of the helicopter is much higher than of a typical research aircraft (c.f. Siebert et al., 2021, sidebar "Profiling with aircraft and helicopter"), so the averaging in horizontal is rather limited in comparison with typical aircraft data.

We commented on this issue in sec. 5.3.:

In contrast to the PROFs, the LEG-derived exponents stay mostly close to  $2/3$  or  $-5/3$ , accordingly, while the correlations are close to one. We suppose that the observed discrepancy results from the combination of horizontal inhomogeneity and intermittency of turbulence. PROF-derived and LEG-derived parameters should not be directly compared because they represent small and large fluid volumes, respectively. Unfortunately, none of the horizontal segments was performed in the SBL.

16. Line 555: 'which suggests important contribution of moisture to buoyancy' – I agree, but this could be evaluated properly. Buoyancy flux (virtual potential temperature flux) can be broken down into the sensible and latent heat contributions and their ratio determined.

We evaluated the terms contributing to virtual potential temperature flux using the approximation valid under dry conditions (e.g De Roode and Duynkerke, 1997):

$$\langle w' \theta'_v \rangle = \langle w' \theta' \rangle + \theta \varepsilon \langle w' q'_v \rangle \quad (3)$$

where  $\varepsilon = R_v/R_d - 1$ . The results listed in the table below confirm that the moisture term plays a significant role in the lower part of the boundary layer.

The information about this fact was added to sec. 5.2 and sec.6.

At low levels in the atmosphere (at the surface and in LEG307) the contribution of moisture transport to buoyancy is of the same order as the contribution of heat transport (not shown).

In the lower part of the STBL (at the surface, in LEG143 and LEG287) the contribution of moisture transport to buoyancy is of the same order as the contribution of heat transport (not shown).

In both cases, latent heat flux qualitatively resembles the profile of  $B$  which is consistent with the considerable contribution of moisture transport to buoyancy in the lower part of the STBL.

### Minor issues (grammar, typos, etc)

While overall, the manuscript is clear and well written, there are many minor grammatical issues – notably missing definitive articles: '... in the cloud top region...', '... in the inertial subrange...' etc. I have noted all those that jumped out at me below, but I'm sure I've missed more.

**Table 8.** Contributions to virtual potential temperature flux inside the boundary layer. Left column for each term is a LEG-derived value, right column is the variability among subsegments.

	Height [m]	$\langle w'\theta' \rangle$ [ $10^{-3}\text{mK s}^{-1}$ ]	$\varepsilon\theta\langle w'q'_v \rangle$ [ $10^{-3}\text{mK s}^{-1}$ ]		
Flight #5	0	9.0	-	7.6	-
	307	3.4	2.2	3.0	1.4
	553	6.1	5.6	0.3	1.4
	819	33.1	17.8	6.5	4.8
Flight #14	0	5.5	-	6.3	-
	143	7.4	2.7	4.6	2.1
	287	1.4	3.4	2.4	1.7
	448	3.1	2.3	0.4	2.7
	992	2.2	3.4	0.7	1.5

We are impressed by the language editing provided by the reviewer. As we are not native speakers, we rely on him and applied all the minor corrections suggested.

1. Line 4: ‘...in cloud top region’ -> ‘...in the cloud top region’

Corrected.

2. Line 12: ‘in inertial subrange’ -> ‘in the inertial subrange’

Corrected.

3. Line 22: ‘They occupy..., preferably in the conditions of large-scale subsidence.’ – ‘preferably’ is the wrong word (implies an ideal choice or active preference’, ‘preferentially’ is closer to the meaning required (with greater likelihood)

Changed to ‘preferentially’.

4. Line 28: ‘Primary mechanism...’ -> ‘The primary mechanism...’

Corrected.

5. Line 29: ‘Additional source of turbulence...’ -> ‘An additional source of turbulence...’

Corrected.

6. Line 32: ‘...dependent on the level in which SC is coupled...’ – ‘in’ isn’t the right word here, and the meaning intended isn’t entirely clear, either ‘...dependent on the level at which SC is coupled...’ (if the issue of concern is the altitude

at which decoupling occurs) or ‘...dependent on the level to which SC is coupled...’ (if the issue is whether, or how strongly decoupled the BL is).

Changed to ‘to which’.

7. Line 35: ‘...structure features adiabatic lapse rate (dry below cloud, moist inside), strong capping inversion at the top, near-constant concentration of moist-conserved variables...’ -> ‘...structure features an adiabatic lapse rate (dry below cloud, moist inside), a strong capping inversion at the top, and near-constant concentration of moist-conserved variables...’

Corrected.

8. Line 40: ‘Stable or...’ -> ‘A stable or...’

Corrected.

9. Line 62: ‘...in conventional rationale...’ -> ‘...in the conventional rationale...’

Corrected.

10. Line 105: ‘...depended on local cloud...’ -> ‘...depended on the local cloud...’

Corrected.

11. Line 106: ‘usual strategy involved:...’ -> ‘the usual strategy involved...’

Corrected.

12. Line 109: ‘...and flight pattern...’ -> ‘...and a flight pattern...’

Corrected.

13. Line 140: ‘Brunt-Vaisala frequency...’ -> ‘The Brunt-Väisälä frequency...’

Corrected.

14. Line 143: ‘...quantifies vertical gradient...’ -> ‘...quantifies the vertical gradient...’

Corrected.

15. Line 166: ‘...as BL mean.’ -> ‘...as the BL mean.’

Corrected.

16. Line 183: ‘...where it features the increase of...’ -> ‘...where it features an increase of...’

Corrected.

17. And ‘...analogously, with the decrease of...’ -> ‘...analogously, with a decrease of...’

Corrected.

18. Line 184-185: ‘... capped by the layer of...’ -> ‘... capped by a layer of...’  
Corrected.
19. Line 239: ‘Described modification...’ -> ‘The modification described...’  
Corrected.
20. Line 243: ‘... with simple...’ -> ‘... with a simple...’  
Corrected.
21. Line 244: ‘... from original signal.’ -> ‘... from the original signal.’  
Corrected.
22. Line 249: ‘... taking average along LEG...’ -> ‘... taking the average along the leg...’  
Corrected.
23. Line 252: ‘Worth to remember...’ -> ‘It is worth remembering...’  
Corrected.
24. Line 260: ‘... such approach...’ -> ‘... such an approach...’  
Corrected.
25. Line 266: ‘Range of scales...’ -> ‘The range of scales...’  
Corrected.
26. Line 266: ‘... limited by the smaller among spatial resolutions of two multiplied signals...’ the word smaller here might be read as implying the smaller scale (ie, higher resolution), suggest -> ‘... limited by the lowest spatial resolution of the two multiplied signals...’  
Corrected.
27. Line 267-268: following the previous statement, you note the scales of individual measurements, but it would be helpful to be explicit and state the resulting scale for the final fluxes.  
Sentence added: ‘As a result,  $\langle w'\theta' \rangle$ ,  $\langle w'u' \rangle$  and  $\langle w'\theta' \rangle$  are resolved down to  $\sim 0.5$  m while  $\langle w'q'_v \rangle$  down to  $\sim 1$  m.’
28. Line 317: ‘In case of LEGs...’ -> ‘In the case of LEGs...’  
Corrected.
29. Line 338: ‘Similar approach...’ -> ‘A similar approach...’  
Corrected.

30. Line 340: ‘Such value of...’ -> ‘Such a value of...’  
Corrected.
31. Line 345: ‘Integral lengthscale...’ -> ‘The integral length scale...’  
Corrected.
32. Line 347: ‘... integral of autocorrelation function...’ -> ‘... integral of the autocorrelation function...’  
Corrected.
33. ‘... in formal definition...’ -> ‘... in the formal definition...’  
Corrected.
34. Line 353: ‘At Taylor microscale...’ -> ‘At the Taylor microscale...’  
Corrected.
35. Line 365-366: The statement ‘Depending on flight segment type, they are illustrated with continuous profiles (PROF) and/or dots with errorbars (LEG).’ Is redundant, delete.  
Ok, removed.
36. Line 372: ‘... reaches minimum value...’ -> ‘... reaches a minimum value...’  
Corrected.
37. Line 387: ‘... resemble typical mixed layer...’ -> ‘... resemble a typical mixed layer...’  
Corrected.
38. Line 390: ‘... exhibit maximum...’ -> ‘... exhibit a maximum...’  
Corrected.
39. Line 398-399: The statement ‘while the shear production at the bottom and at the top of the boundary layer’ is incomplete... needs some statement about the shear production.  
Corrected to ‘while the shear production is expected to be significant at the bottom and at the top of the boundary layer’.
40. Lines 395, 402, 406: statements about results are phrased as ‘seems to’, ‘appears to be’ etc. Unless there is real doubt, be definitive... is it as stated or not?  
Corrected. Speculative verbs were removed.
41. Line 495: ‘... immensely stable...’ -> ‘... strongly stable...’ (immensely might be overstating things a bit).  
Corrected.

42. Line 561: ‘...vanishes at the level...’ -> ‘...vanishes at a level...’

Corrected.

43. Line 568-569: ‘Vertical velocity variance suggests the profile somewhat different than the convective similarity scaling’  
-> ‘The vertical velocity variance suggests a profile somewhat different than the convective similarity scaling’

Corrected.

44. Line 659: ‘Main processes...’ -> ‘The main processes...’

Corrected.

45. Line 669: ‘imortant’ -. ‘important’

Corrected.

46. Line 670: ‘relevant systematical...’ – ‘...relevant systematic...’

Corrected.

### Additional corrections

1. While revising the manuscript, we found a mistake regarding the wind direction given in sec. 3.3 and 3.4. The correct wind direction is from the NNW in the coupled STBL and from the NW in the decoupled STBL.
2. In the discussion of spectral anisotropy (Figs. 17 and 18, sec. 5.4), we changed the term ‘wavelength’ into ‘scale’ when we refer to the separation distance  $r$  in order to avoid any confusion with gravity waves analyses.
3. We applied a few minor corrections in the abstract and section titles to improve the clarity.

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# Coupled and decoupled stratocumulus-topped boundary layers: turbulence properties

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**Abstract.** We compare turbulence properties in ~~two cases of marine~~ coupled and decoupled marine stratocumulus-topped ~~boundary layer, coupled (CP) and decoupled (DCP),~~ boundary layers (STBLs) using high resolution in situ measurements performed by the helicopter-borne platform ACTOS in the region of Eastern North Atlantic.

~~Thermodynamically~~ The thermodynamically well-mixed CP-coupled STBL was characterized by ~~large a comparable~~ latent heat flux at the surface and in the cloud top region, and substantially smaller sensible heat flux in the entire depth. Turbulence kinetic energy (TKE) was efficiently generated by buoyancy in the cloud and at the surface, and dissipated with comparable rate across the entire depth. Structure functions and power spectra of velocity fluctuations in the inertial range were reasonably consistent with the predictions of Kolmogorov theory. The turbulence was close to isotropic.

In the ~~DCP~~ decoupled STBL, decoupling was most obvious in humidity profiles. Heat fluxes and buoyant TKE production at the surface were similar to the CP-coupled case. Around the transition level, latent heat flux decreased to zero and TKE was consumed by weak stability. In the cloud top region heat fluxes almost vanished and buoyancy production was significantly smaller than for the CP-coupled case. TKE dissipation rate inside the ~~DCP differed~~ decoupled STBL varied between its sublayers. Structure functions and power spectra in the inertial range deviated from Kolmogorov scaling. This was more pronounced in the cloud and subcloud layer in comparison to the surface mixed layer. The turbulence was more anisotropic than in the CP-coupled STBL, with horizontal fluctuations dominating. The degree of anisotropy was largest in the cloud and subcloud layer of the ~~DCP~~ decoupled STBL.

Integral ~~lengthscales~~ length scales, of the order of 100 m in both cases, indicate turbulent eddies smaller than the depth of the CP-coupled STBL or of the sublayers of the ~~DCP~~ decoupled STBL. We hypothesize that turbulence produced in the cloud or close to the surface is redistributed across the entire CP-coupled STBL but rather only inside the ~~relevant sublayers in the~~ DCP sublayers where it was generated in the case of the decoupled STBL. Scattered cumulus convection, developed below the stratocumulus base, may play a role in transport between those sublayers.

## 1 Introduction

Low-level stratocumulus clouds (~~SCs~~) cover around 20 % of the Earth's surface in annual mean, more than any other cloud type. They occupy upper few hundred meters of the planetary boundary layer (~~BL~~), ~~preferably~~, preferentially in the conditions

25 of large-scale subsidence, strong lower-tropospheric stability and moisture supply from the surface (Wood, 2012). Those are usually present in the regions of subtropical and midlatitude oceans with upwelling of cold deep water. Wide-spread presence, persistence and high albedo makes marine stratocumulus important for the energy balance of the planet (Hartmann et al., 1992). Minor variations in coverage and optical thickness impact the radiation budget, therefore also model-based climate predictions (Boucher et al., 2013; Schneider et al., 2019).

30 ~~Primary~~ The primary mechanism driving the circulation inside stratocumulus-topped boundary layer (STBL) is longwave radiative cooling at the cloud top which produces convective instability. ~~Additional~~ An additional source of turbulence is provided by surface buoyancy, wind shear, latent heat release in updrafts, evaporation in downdrafts or evaporative cooling associated with entrainment of dry, warm air from the free troposphere (Lilly, 1968; Stevens, 2002; Gerber et al., 2016; Mellado, 2017). Properties of the STBL are dependent on the level ~~in which SC~~ to which stratocumulus cloud is coupled with  
35 sea surface fluxes, in particular of latent and sensible heat (Bretherton and Wyant, 1997; Xiao et al., 2011; Zheng et al., 2018a).

Moderately shallow STBLs are often well mixed (Stull, 1988; Markowski and Richardson, 2010). Their typical vertical structure features an adiabatic lapse rate (dry below cloud, moist inside), a strong capping inversion at the top, near-constant concentration of moist-conserved variables (such as total water mass fraction and liquid water potential temperature) from the surface up to the inversion. However, when the circulation ceases to mix the air over entire depth, the STBL becomes  
40 decoupled, i.e. the cloud is separated from the moisture supply from the surface (Nicholls, 1984; Turton and Nicholls, 1987; Wood, 2012). ~~Radiatively driven SC-containing~~ The radiatively driven stratocumulus layer (SCL) and the subcloud layer (SBL) in the upper part might be still mixed by negatively buoyant eddies generated at cloud top while the surface mixed layer (SML) at the bottom by positive buoyancy or shear. ~~Stable~~ A stable or conditionally unstable intermediate transition layer (TSL) emerges in between. Conditional instability allows for the cumulus updrafts to penetrate through and intermittently restore the  
45 coupling (Bretherton and Wyant, 1997; De Roode and Duynkerke, 1997).

Decoupling can be caused either by reducing the intensity of radiatively driven circulation in relation to STBL depth or by stabilizing the subcloud layer (Zheng et al., 2018b). The first possibility might be realized with daytime shortwave radiative heating which offsets longwave cooling (Nicholls, 1984; Turton and Nicholls, 1987) or by extensive entrainment of warm and dry free-tropospheric air which deepens the STBL to such an extent that the turbulence is no longer sufficient to sustain the  
50 mixing (Bretherton and Wyant, 1997). The second possibility involves stratification of the lower part by cooling, for instance due to precipitation evaporation (Caldwell et al., 2005; Dodson and Small Griswold, 2021) or advection over colder sea surface (Stevens et al., 1998).

SC-STBL decoupling is the factor which strongly influences further evolution of cloud pattern and boundary layer structure. It constitutes an intermediate stage of transition from overcast stratocumulus into shallow cumulus convection over subtropical  
55 oceans as the air masses are advected by the trade winds towards the equator (Albrecht et al., 1995; Bretherton and Wyant, 1997; De Roode et al., 2016; Zheng et al., 2020). Successful representation and prediction of such transition between the two STBL regimes pose a challenge for atmospheric general circulation models (Xiao et al., 2012), in large part due to limited understanding of the interaction of various processes involved.

60 Previous observational studies have documented the structure of the coupled and decoupled STBLs in terms of thermodynamic and radiative features (Wood and Bretherton, 2004; Jones et al., 2011; Ghate et al., 2015; Zheng and Li, 2019) as well as aerosol and cloud properties (Dong et al., 2015; Wang et al., 2016; Goren et al., 2018; Zheng et al., 2018b). On the other hand, modeling efforts provided insightful conceptual explanations of the mechanisms leading to a switch between coupled and decoupled regimes (Turton and Nicholls, 1987; Bretherton and Wyant, 1997; Stevens, 2000; Xiao et al., 2011).

65 Although the concept of circulation and turbulence being insufficiently strong in order to maintain the mixing throughout the entire depth plays a central role in [the](#) conventional rationale of decoupling, few works attempted to quantitatively characterize small-scale (integral ~~lengthscales~~ [length scales](#) and below) turbulence (e.g. Lambert and Durand, 1999; Dodson and Small Griswold, 2021). The major reason is the technical difficulty in measuring turbulent fluctuations of wind velocity, temperature or humidity with adequate spatial resolution and accuracy. Within the present study, we compare the properties of turbulence derived from unique helicopter-borne observations performed in coupled and decoupled STBL in the region of Eastern North Atlantic. Particular attention is given to small-scale features and deviations from the assumption of stationary homogeneous isotropic turbulence.

75 The paper is structured as follows. Section 2 introduces the measurements, including instrumentation, sampling strategy and general synoptic conditions. The selection of the two cases, coupled and decoupled STBL, is explained. Section 3 describes the stratification of the STBL in terms of thermodynamics and stability. The division into sublayers is delineated and the degree of coupling is expressed quantitatively according to literature criteria. Section 4 provides relevant details concerning derivation of turbulence parameters. Section 5 compares properties of turbulence: turbulence kinetic energy, its production and dissipation rates, fluxes of sensible and latent heat, anisotropy of turbulent motions, typical ~~lengthscales~~ [length scales](#). Finally, the results of the comparison are summarized and discussed in the last section.

## 2 Measurements

### 80 2.1 Location and synoptic conditions

Observations were collected in July 2017 during the ACORES (Azores stratoCumulus measurements Of Radiation, turbulEnce and aeroSols) campaign in the Eastern North Atlantic (~~ENA~~) around the island of Graciosa in the Azores archipelago. Comprehensive description of the project, including weather conditions, instrumentation, sampling strategy and selected research highlights is provided by Siebert et al. (2021).

85 The area of the experiment is considered to be influenced by a wide range of synoptic scale meteorological conditions. Graciosa is located near the boundary of subtropics and mid-latitudes. Therefore, the impacts of both subtropical trade wind system and mid-latitude cyclones are relevant. The climatology of the marine boundary layer was inferred by Rémillard et al. (2012) based on the long-term ground-based measurements of CAP-MBL project (Wood et al., 2015) utilizing the Atmospheric Radiation Measurement (ARM) facility established right next to the Graciosa airport. They reported that ~~BL~~ [boundary layer](#) decoupling and multiple cloud types (for instance cumulus under stratocumulus) are very frequent at the site throughout the

year. Indeed, the range of weather conditions was observed during the ACORES, related to the location and strength of Azores high, as well as occasional front passages (Siebert et al., 2021).

## 2.2 Instrumentation

95 Measurements were performed with the Airborne Cloud Turbulence Observations System (ACTOS, [?Siebert et al. \(2006a\)](#)) and the Spectral Modular Airborne Radiation measurement system - HELICOPTER-borne ObservationS (SMART-HELIOS, Werner et al. (2013, 2014)). Both instrumental payloads were carried by the helicopter BO-105 as two separate external cargos on one long tether: SMART-HELIOS mounted 20 m below the helicopter and ACTOS another 150 m underneath. Typical true air speed (~~TAS~~) of  $20 \text{ m s}^{-1}$  and high sampling rate of individual instruments provided spatial resolution much higher than for a typical research aircraft.

100 For complete instrumentation of the helicopter payloads see Tables 1 and 2 in Siebert et al. (2021). In the current study we used the following ACTOS data: three-dimensional wind vector  $(u_e, v_e, w_e)$  in the Earth-fixed system and longitudinal-vertical wind components  $(u, w)$  in platform-fixed system (derivation explained in sec. 4) provided by the combination of the ultrasonic ~~anemometer~~ ~~anemometer-thermometer~~ (Gill Solent HS, [Siebert and Teichmann \(2000\)](#)) and a high-accuracy motion package (inertial navigation system and GPS); ~~virtual temperature  $T_v$  derived from the speed of sound measured with the same ultrasonic~~ ~~anemometer-thermometer~~ ([Siebert and Muschinski, 2001](#)); temperature  $T$  and its small scale fluctuations measured by the Ultra-Fast Thermometer (~~Haman et al., 1997; Nowak et al., 2018~~) ([UFT, Haman et al. \(1997\); Nowak et al. \(2018\)](#)) combined with the precise calibrated PT100; specific humidity  $q_v$  from the [open-path](#) infrared absorption hygrometer (~~LICOR-7500~~ [LI-COR LI-7500](#), Lampert et al. (2018)); liquid water ~~content~~ ~~mass fraction~~  $q_l$  determined with the Particle Volume Meter (PVM-100A, Gerber et al. (1994); Wendisch et al. (2002)).

110 [The standard deviations due to uncorrelated noise for sonic measurements are  \$0.02 \text{ m s}^{-1}\$  for wind and  \$0.02 \text{ K}\$  for virtual temperature \(Siebert and Muschinski, 2001\). The PT100 was calibrated prior to the campaign in a thermostated water tank using the Greisinger GMH 3750 reference thermometer which provides accuracy better than  \$0.05 \text{ K}\$ . The UFT was calibrated for each flight separately against the PT100. For the UFT records, the standard deviation due to uncorrelated noise is  \$4 \text{ mK}\$  \(Siebert et al., 2003\). The hygrometer provides  \$q\_v\$  with a noise floor of about  \$0.005 \text{ g kg}^{-1}\$ . This instrument was verified](#)  
115 [to agree well with a few hygrometers of different types and operate satisfactorily on the helicopter-towed system Helipod by Lampert et al. \(2018\). The PVM-100A measures  \$q\_l\$  with the accuracy of 5 % and its noise floor was estimated by Siebert et al. \(2003\) to be about  \$0.001 \text{ g kg}^{-1}\$ . The exact sensitivity depends to some extent on droplet size distribution, see Wendisch et al. \(2002\) for details. For a more general discussion of the instrumentation on the ACTOS platform see Siebert et al. \(2006a\).](#)

## 2.3 Data overview

120 Helicopter flights during ACORES were typically performed over the ocean inside the 10 by 10 km square adjacent to the northern coast of Graciosa. Specific flight path and maneuvers depended on [the](#) local cloud situation. Within the flight time of two hours, [the](#) usual strategy involved: vertical profile up to roughly 2000 m (a.s.l.), a few 10 km long horizontal legs at selected levels and several steep porpoise dives around ~~SC~~ ~~stratocumulus~~ top. Two flights were selected for our comparative study: flight

#5 on 8 July 2017 and flight #14 on 18 July 2017. The choice was dictated by SC-stratocumulus presence, STBL stratification (considerably well-mixed in flight #5, considerably decoupled in flight #14) and a flight pattern involving substantial sampling time below SC.

Segments of two types were selected from ~~of~~ the measurement records: profiles (PROFs) and horizontal legs (LEGs). For convenience, ~~they are ordered for each flight~~ PROFs are ordered chronologically according to their time of execution and referred to as PROF1-PROF5 ~~and LEG1-LEG5, for each flight~~ while LEGs are ordered according to their mean altitude (m above sea level). The segmentation was done manually so that the influence of sharp turns and pendulum-like motion of the payload is ~~minor~~ avoided. This resulted in the reduced length of the LEGs, between 3.5 and 12 km. LEGs were flown with a true air speed of 15-20 m s<sup>-1</sup> and some minor displacements in vertical are unavoidable for the payload on a 170 m long rope. The mean altitudes and exact lengths are listed in Table 1. PROFs are in fact slanted with an ascent or descent rate of about 3-5 m s<sup>-1</sup> ~~and TAS ~20~~ which results in an aspect ratio of 0.15-0.25. The horizontal component of motion is necessary to avoid the downwash of the helicopter affecting wind and turbulence measurements on ACTOS. ~~LEGs were flown with TAS of 15-20 and some minor displacements in vertical are unavoidable for the payload on a 170 long rope. More details about measuring turbulence below a helicopter can be found in Siebert et al. (2006a); Muschinski et al. (2001).~~

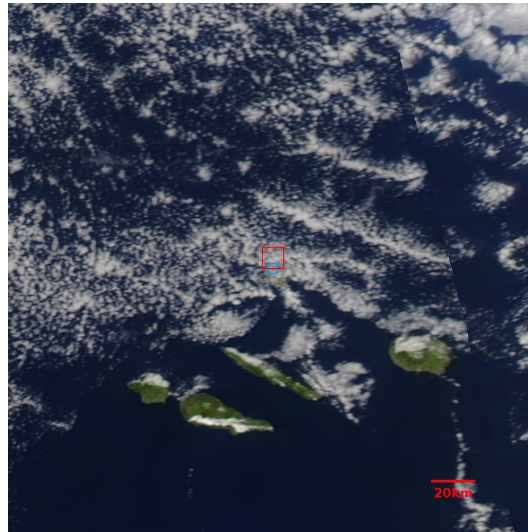
**Table 1.** Mean altitude and length of the LEGs.

	Height [m]	Length [km]
Flight #5	<u>307</u>	<u>5.44</u>
	<u>553</u>	<u>5.51</u>
	<u>819</u>	<u>7.93</u>
	<u>1079</u>	<u>3.94</u>
	<u>2018</u>	<u>6.25</u>
Flight #14	<u>143</u>	<u>8.11</u>
	<u>287</u>	<u>11.92</u>
	<u>448</u>	<u>7.10</u>
	<u>992</u>	<u>4.79</u>
	<u>2021</u>	<u>3.49</u>

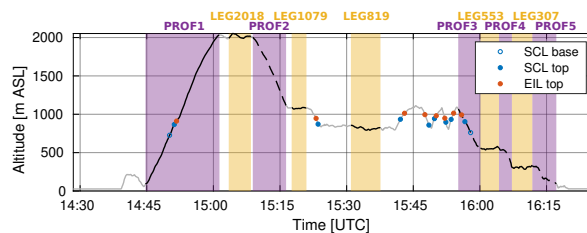
Flight #5 was performed in the afternoon (14:28-16:26 UTC<sup>1</sup>) on 8 July 2017. Stratocumulus clouds emerged behind the cold front which had passed the island the day before. The cloud field was moderately thick and quite heterogeneous in structure, with some visible clearings. Satellite image from MODIS on Aqua (Fig. 1) confirms this observation showing dispersed cloud patches in the vicinity of Graciosa. The flight pattern (Fig. 2) involved: deep PROF from minimum flight level (60 m) into the free troposphere (FT), two LEGs in the FT with one close to SC-the stratocumulus top, three LEGs in the STBL with one

<sup>1</sup>On Azores the local time in summer is equivalent to UTC.

inside SEstratocumulus cloud, close to its top. Specific PROFs are indicated in the figure with different line styles which are used hereafter in the vertical profiles of various derived parameters. Altitude ranges corresponding to PROF2-PROF5 of this flight do not overlap, hence we marked them all with dashed lines.



**Figure 1.** Satellite true color image (250 x 250 km) from MODIS taken on Aqua overpassing Azores 8 July 2017 at 15:45 UTC (i.e. during flight #5, the time given corresponds to the left swath covering most of the image) by the MODIS instrument on Aqua overpassing Azores, centered on Graciosa airport (blue circle), with overlaid helicopter operation area (red box). The image was acquired from NASA Worldview Snapshots.

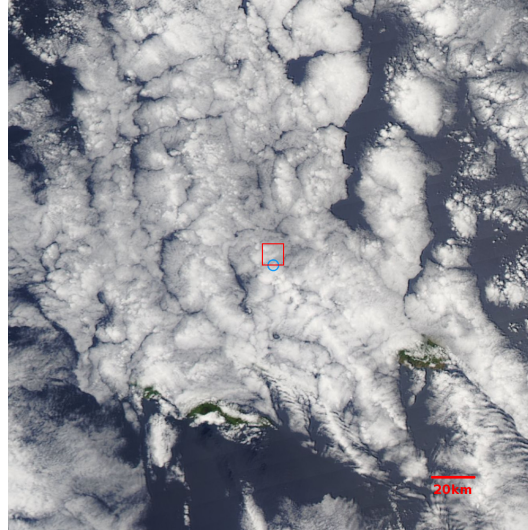


**Figure 2.** ACTOS altitude in flight #5 with marked selected profiles (purple) and horizontal legs (yellow). PROFs are ordered chronologically, LEGs are ordered according to their altitude. Line style styles of the profiles is PROFs are consistent with the figures in following sections. Altitude ranges corresponding to PROF2-PROF5 of this flight do not overlap and are all marked with dashed lines. Dots indicate the penetrations of the boundaries of the specific sublayers described in sec. 3.

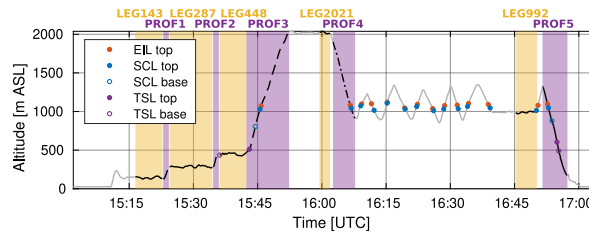
Flight #14 was performed in the afternoon (15:01-17:04 UTC) on 18 July 2017, shortly after weak precipitation had been noted at the site. The sky was overcast with SEstratocumulus cloud of homogeneous structure. Many little cumulus clouds, probably at the initial state of formation, were reported over the ocean below SEstratocumulus deck. However, they were not



observed to reach SE-stratocumulus base. MODIS Aqua image (Fig. 3) shows large solid patch of SE-stratocumulus clouds with signatures of closed-cell convection regime. The flight pattern (Fig. 4) involved: four LEGs in the STBL with one inside SEthe stratocumulus cloud, close to its top, one LEG in the FT and a number of PROFs connecting LEG levels. In this figure and hereafter, PROF1-PROF3 are all marked with dashed lines because their altitude ranges do not overlap.



**Figure 3.** As in Fig. 1 but for-taken on 18 July 2017 at 14:43 UTC (shortly before flight #14.-14). The image was acquired from NASA Worldview Snapshots.



**Figure 4.** As in Fig. 2 but for flight #14. Line styles of the PROFs are consistent with the figures in following sections. PROF1-PROF3 are all marked with dashed lines because their altitude ranges do not overlap.

### 3 Stratification

#### 3.1 Derivation of meteorological and stability parameters

155 Meteorological conditions and stability parameters derived from PROFs are shown in Fig. 5 and Fig. 6 for flight #5 and #14, respectively. Liquid water potential temperature  $\theta_l$  was calculated following the approximation by Betts (1973):

$$\theta_l = \theta - \frac{\theta}{T} \frac{L_v}{c_p} q_l \quad (1)$$

where  $\theta$  denotes potential temperature,  $L_v$  latent heat of vaporization for water and  $c_p$  specific heat of dry air at constant pressure. Horizontal wind speed  $U$  and direction  $dd$  result from appropriate transformation of measured flow velocity (Edson  
160 et al., 1998). Because helicopter climb rate was not exactly constant in time and individual instruments differ in sampling rate, data points were grouped and averaged in 10 m high altitude bins (yet separately for each PROF). To reduce the effect of random eddy penetration and improve clarity, wind profiles were additionally smoothed with five point moving average.

Lifting condensation level (LCL) was then derived for each height according to Bolton (1980). Such result is sensitive to gradients of thermodynamic properties in subcloud layer, signaling the degree of ~~BL~~ boundary layer coupling. To characterize  
165 static stability, the Brunt-Vaisala frequency  $N_b$  was used:

$$N_b^2 = \frac{g}{\theta_v} \frac{\partial \theta_v}{\partial z} \quad (2)$$

where  $\theta_v$  is virtual potential temperature derived from speed of sound (provided by ultrasonic anemometer),  $g$  gravitational acceleration and  $z$  height above sea level. Shear rate  $Sh$  quantifies the vertical gradient of horizontal wind:

$$Sh^2 = \left( \frac{\partial u_e}{\partial z} \right)^2 + \left( \frac{\partial v_e}{\partial z} \right)^2 \quad (3)$$

170 where  $u_e$  is eastward and  $v_e$  northward wind component. The derivatives were evaluated as the tangent of linear least-square fit of 10 m binned variable versus  $z$  performed inside symmetric five point windows.

#### 3.2 Quantitative judgement of the degree of coupling

In order to objectively confirm the fact of coupling or decoupling of STBL, we employed several methods from the literature  
175 ~~: Jones et al. (2011), hereafter J11, Wood and Bretherton (2004), hereafter WB04, Yin and Albrecht (2000), hereafter YA00~~ (Jones et al., 2011; Wood and Bretherton, 2004; Yin and Albrecht, 2000).

~~First criterion of J11~~ The first criterion of Jones et al. (2011) involves the differences of  $\theta_l$  and total water ~~content~~  $q_t = q_l + q_v$   
mixing ratio between the uppermost and the lowermost quarters of ~~BL~~ the boundary layer (instead of the latter quantity, we  
used our total water mass fraction  $q_t = q_l + q_v$  which does not influence the conclusions because those two measures are  
approximately equal). The sounding is classified as coupled when  $\Delta\theta_l = \theta_l^{top} - \theta_l^{bot} < 0.5$  K and  $\Delta q_t = q_t^{bot} - q_t^{top} < 0.5$  g kg<sup>-1</sup>,  
180 decoupled otherwise. ~~Second criterion of J11~~ The second criterion of Jones et al. (2011) involves the difference between the  
observed cloud base height ~~(CB)~~ CB and the LCL corresponding to the conditions at ~~BL bottom~~. ~~The BL~~ the bottom of

the boundary layer. It is classified as coupled when  $\Delta z = \text{CB} - \text{LCL}^{bot} < 150$  m, decoupled otherwise. Here, we used mean conditions of the lowest leg (~~LEG5-LEG307~~ for flight #5, ~~LEG1-LEG143~~ for flight #14) to estimate  $\text{LCL}^{bot}$  and  $q_l$  in PROFs to estimate ~~CB~~the cloud base height.

185 ~~WB04~~Wood and Bretherton (2004) proposed two decoupling parameters:

$$\alpha_\theta = \frac{\theta_l^- - \theta_l^0}{\theta_l^+ - \theta_l^0} \quad \alpha_q = \frac{q_t^- - q_t^0}{q_t^+ - q_t^0} \quad (4)$$

where superscripts +, -, 0 denote the values just above the inversion, just below the inversion and in the surface mixed layer, respectively. ~~WB04~~Wood and Bretherton (2004) calculated  $\alpha_\theta$  and  $\alpha_q$  over subtropical Eastern Pacific at around 0 to 0.4, however no exact critical value for decoupling was determined. The higher those parameters, the more decoupled ~~BL~~boundary layer is considered. Here, instead of finding first the SML, we apply mean values in the lower quarter of the ~~BL~~boundary layer ( $\theta_l^0 = \theta_l^{bot}$  and  $q_t^0 = q_t^{bot}$ ).

~~YA00~~Yin and Albrecht (2000) introduced a stability parameter to identify transitions in ~~BL-soundings~~boundary layer soundings:

$$\mu = -\frac{\partial \theta}{\partial p} + \frac{\varepsilon \theta}{1 + \varepsilon r} \frac{\partial r}{\partial p} - \frac{\varepsilon \theta}{1 + \varepsilon r_v} \frac{\partial r_v}{\partial p} \quad (5)$$

195 where  $\varepsilon = R_v/R_d - 1$  depends on the ratio of gas constants for water vapor  $R_v$  and dry air  $R_d$ , while  $r_v$  is water vapor mixing ratio. Their procedure detects transition anytime in the subcloud zone the value of  $\mu$  exceeds by a factor of 1.3 the average  $\bar{\mu}$  between 980 and 900 hPa. Here, instead of using pressure levels, we specify  $\bar{\mu}$  as ~~BL~~the boundary layer mean.

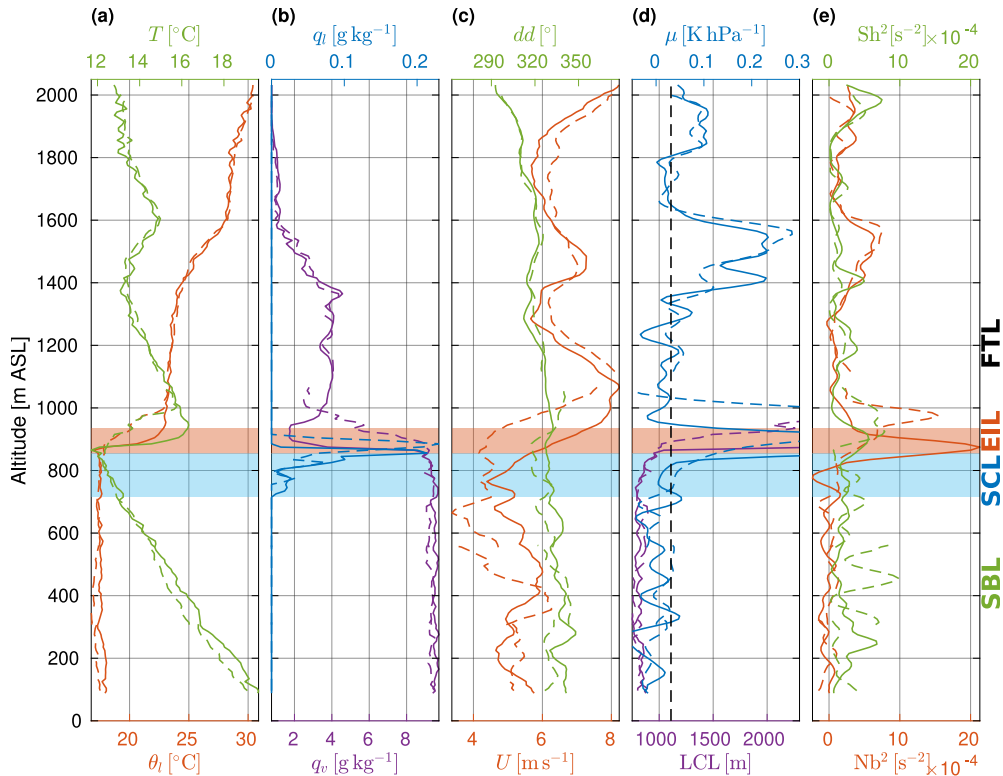
The above parameters were estimated using PROF1 of flight #5 and PROF5 of flight #14. According to ~~JH~~criteriathe criteria of Jones et al. (2011), it is evident that flight #5 ( $\Delta\theta_l = -0.51^\circ\text{C}$ ,  $\Delta q_t = 0.13 \text{ g kg}^{-1}$ ,  $\Delta z = -72$  m) was performed in a coupled STBL while flight #14 ( $\Delta\theta_l = 1.19^\circ\text{C}$ ,  $\Delta q_t = 0.90 \text{ g kg}^{-1}$ ,  $\Delta z = 216$  m) in a decoupled STBL. Negative values of  $\Delta\theta_l$  and  $\Delta z$  suggest instability but it might be also attributed to horizontal inhomogeneities of ~~SC~~stratocumulus structure (sec. 2.3) in combination with slanted flight path. Consistently, ~~WB04-parameters~~the parameters of Wood and Bretherton (2004) are smaller for flight #5 ( $\alpha_\theta = -0.12$ ,  $\alpha_q = 0.04$ ) than for flight #14 ( $\alpha_\theta = 0.26$ ,  $\alpha_q = 0.26$ ). The parameter ~~of YA00~~ $\mu$  is plotted in panel (d) of Figs. 5 and 6. It varies significantly with height and the critical value is occasionally exceeded in both flights. 205 This method was probably optimized for radiosoundings in different climate regime and does not seem robust in case of our data.

Following previous studies looking for differences of cloud top entrainment instability (~~CTEI~~) between coupled and decoupled ~~SC~~clouds (e.g. Xiao et al., 2011), we calculated the Randall-Deardorff parameter (Randall, 1980; Deardorff, 1980):

$$210 \quad \kappa = 1 + \frac{c_p}{L_v} \frac{\theta_l^+ - \theta_l^-}{q_t^+ - q_t^-}. \quad (6)$$

In both our cases ( $\kappa = 0.71$  for flight #5 and  $\kappa = 0.34$  for #14), it exceeds the critical value of about 0.23 indicating the possibility of buoyancy reversal resulting from mixing and evaporative cooling at cloud top.

### 3.3 Structure of the coupled STBL



**Figure 5.** Vertical structure of the coupled STBL (flight #5): (a) temperature  $T$  and liquid water potential temperature  $\theta_l$ , (b) liquid water content-mass fraction  $q_l$  and specific humidity  $q_v$ , (c) wind speed  $U$  and direction  $dd$ , (d) lifting condensation level LCL and stability parameter  $\mu$  of Yin and Albrecht (2000) with its critical level for the detection of transitions (dotted-dashed black line), (e) squared Brunt-Vaisala frequency  $Nb^2$  and wind shear rate  $Sh^2$ . Line styles correspond to specific profiles – consistently with Fig. 2. Color shadings denote the sublayers: entrainment interface layer (red) and stratocumulus layer (blue).

The profiles in flight #5 exhibit a well-mixed STBL (Fig. 5). Temperature falls with height with near constant lapse rate  $\Gamma_T$  inside the BL boundary layer, followed by a sharp inversion at the top. Liquid water potential temperature is almost constant from close to the surface up to SC the stratocumulus top, where it features the an increase of  $\sim 5$  K. Total water content-mass fraction behaves analogously, with the a decrease of  $\sim 7$  g kg $^{-1}$  above cloud top. Interestingly, very dry air is located at the top of the temperature inversion. It is further capped by the a layer of considerably higher  $q_v$ , however much lower than inside the BL boundary layer. Liquid water content-mass fraction in the cloud is moderate and suggest non-trivial cloud structure, probably there were some. There were cloud clearings penetrated as ACTOS moved along the slanted path, visible in the high rate records of  $q_l$  (not shown here). Wind velocity fluctuates in the BL boundary layer within  $\pm 1$  m s $^{-1}$  around the mean

$\sim 5 \text{ m s}^{-1}$ . Wind shear across the cloud top and the inversion can be noticed. Wind direction is from the ~~NNE~~NNW throughout the sampled height.

Significant differences can be observed between the PROFs in wind speed and the position of inversion. Subsequent PROFs  
225 were not performed at the same time and location, so certain variability is expected. Airborne sampling features inevitable randomness due to probing specific structures (eddies, updrafts, cloud holes etc.), thus slanted profiles do not represent mean conditions accurately.

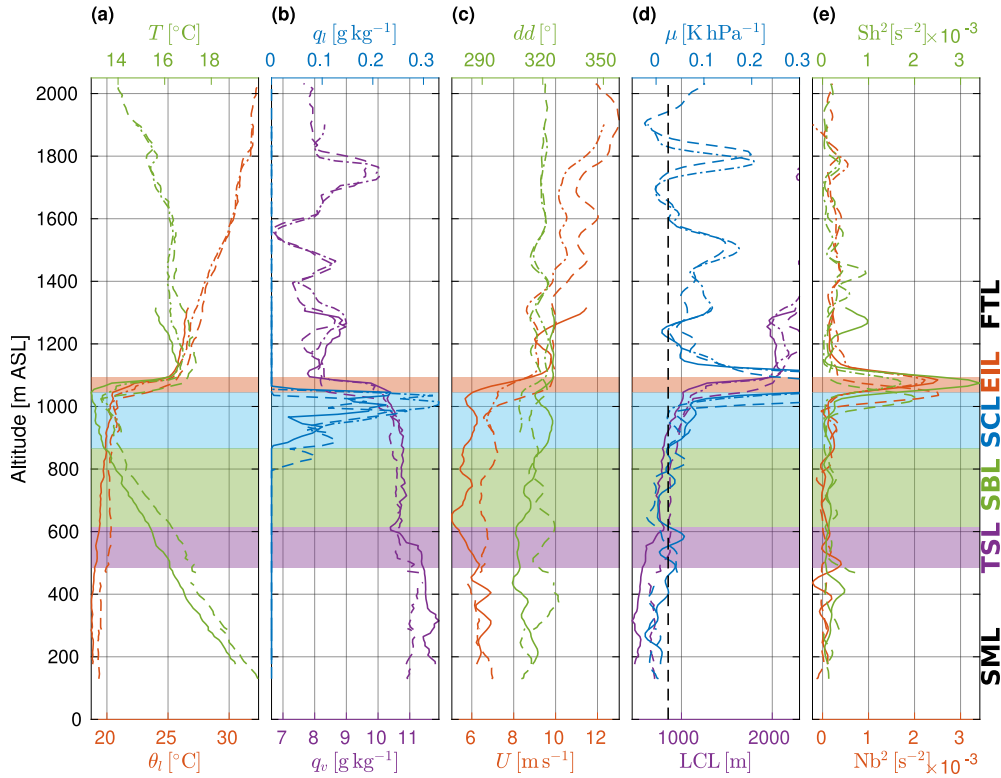
LCL stays roughly equal from the lowest level up to the cloud base. Interestingly, it is slightly higher than the actual ~~CB~~  
cloud base which might be again related to horizontal inhomogeneities in cloud structure. Brunt-Vaisala frequency indicates  
230 weak static instability in the ~~BL~~boundary layer, stronger inside the cloud than below, and very strong stability at the capping inversion. Wind shear is more variable which can be attributed to sampling various eddies.

Based on  $\theta_l$ ,  $q_l$  and  $q_v$ , we manually distinguished the following sublayers: the entrainment interface layer (EIL) including the temperature inversion and the very top of the cloud, the stratocumulus layer (SCL) containing the cloud, the subcloud layer (SBL) ranging from cloud base down to the surface, and the sublayer representing free tropospheric conditions (FTL,  
235 not necessarily adjacent to the EIL top). For reference, the EIL and SCL are marked with red and blue shading in Fig. 5 and following. The heights and average properties inside the sublayers are listed in Table A1 in the appendix. The deepest profile (PROF1, solid line), was used for sublayer distinction because the specific heights may vary between ~~PROFs. Suitable normalization and averaging (Ghate et al., 2015) is not possible in our study because other PROFs are not deep enough~~  
the PROFs. The individual penetrations of the sublayer boundaries during other segments (PROFs and dolphin porpoises) are  
240 indicated in Fig. 2.

### 3.4 Structure of the decoupled STBL

The profiles in flight #14 exhibit decoupled STBL (Fig. 6). Liquid water potential temperature gradually rises with height whereas specific humidity decreases step-wise. Despite the distinct  $q_v$  gradient in BL middle, its value in the lowest part and in the subcloud section is relatively stable. This suggests ~~the upper BL portion is internally mixed that both the upper~~  
245 ~~and the lower~~ BL portion is STBL portion are internally mixed. The FT is quite humid, with values of  $q_v$  larger than for flight #5. The difference in  $\theta_l$  at ~~SC~~stratocumulus top is  $\sim 5 \text{ K}$  while in  $q_t$  only  $\sim 3 \text{ g kg}^{-1}$ . The stratocumulus is thicker and more abundant in liquid water than in the previous case. Wind velocity varies  $\pm 1 \text{ m s}^{-1}$  around the mean  $\sim 6 \text{ m s}^{-1}$ . Wind direction is predominantly ~~NENW~~NNW. There is significant wind shear across the inversion, with difference in  $U$  reaching  $\sim 4 \text{ m s}^{-1}$ . LCL replicates the gradients of  $q_v$  in the middle ~~BL~~of the boundary layer. It corresponds to the ~~CB~~cloud base height only in  
250 the section right below the cloud which is a signature of decoupling. Brunt-Vaisala frequency indicates weak static stability throughout most of the profile, including the cloud. Its peak in the inversion layer coincides well with the maximum of  $\text{Sh}^2$ .

Similarly to flight #5, we distinguished the sublayers: the FTL, the EIL, the SCL, and the SBL extending from cloud base down to the level where LCL is no longer in agreement with the observed ~~CB~~cloud base height. In addition, two more sublayers typical for decoupled conditions were introduced: the transition layer (TSL) containing the major gradients in specific humidity  
255 and wind speed, and the surface mixed layer (SML) extending from the surface up to the bend in  $\theta_l$  profile (where it begins to



**Figure 6.** As in Fig. 5 but for the decoupled STBL (flight #14). Line styles are consistent with Fig. 4. Color shadings denote the sublayers: entrainment interface layer (red), stratocumulus layer (blue), subcloud layer (green), transition layer (purple).

rise with height, c.f. Fig. 6a). Somewhat arbitrary boundary of 385 m was chosen to represent the section directly influenced by surface processes. For reference, the EIL, SCL, SBL and TSL are marked with red, blue, green and purple shading, respectively, in Fig. 6 and following. The heights and average properties inside the sublayers are listed in Table A2. PROF5 was used for sublayer identification because it covers most of the STBL depth. [The individual penetrations of the sublayer boundaries during other segments are indicated in Fig. 4.](#)

260

#### 4 **Turbulence properties: methods**[Methods](#)

Parameters of turbulence were derived using high-resolution measurements of wind velocity, temperature and humidity. Depending on the quantity, the results were obtained for PROFs or LEGs specified in sec. 2.3. In case of PROFs, our procedure resembles the approach of Tjernstrom (1993). After timeseries of a parameter had been computed, appropriate segments were extracted and data were averaged in 10 m altitude bins (as in sec. 3.1). For LEGs, full segment was used to calculate a desired parameter. Next, each LEG was divided into 7 subsegments of equal length, overlapping by half of the length, and the

265

very same method was applied to calculate respective quantity in each subsegment. Standard deviation among subsegments is regarded as parameter variability and shown with errorbars in plots.

270 The lateral channel of the ultrasonic anemometer was affected by a substantial level of artificial fluctuations (up to  $1 \text{ m s}^{-1}$  in amplitude) due to instrumental issues. The origin of this problem is under investigation. It seems to appear for true air speed above about  $12 \text{ m s}^{-1}$  which makes it relevant for most of the flight time. Therefore, we applied simplified geometrical transformation to the measured velocity vector, so that high resolution retrieval of wind velocity is possible. In comparison with the standard transformation (Lenschow, 1986), we included pitch rotation but neglected roll and yaw rotations to prevent the lateral channel from coupling with the others. The resulting vector  $(u, v, w)$  can be interpreted as wind velocity in horizontal longitudinal, horizontal lateral and vertical direction, respectively, as long as the platform is not tilted left or right (roll angle is small). This condition was satisfied throughout most of the flight time, except for major turns. For calculating turbulence properties, we selected segments with the roll angle  $< 0.1 \text{ rad}$ . The lateral wind  $v$  cannot be used for turbulence analysis but longitudinal  $u$  and vertical  $w$  are free from the disturbances. ~~Described modification~~ The modification described is not necessary to obtain mean wind profiles  $(U, \sigma)$  because averaging and smoothing is applied anyway (see sec. 3.1).

280 Reynolds decomposition of the signals (c.f Stull, 1988)

$$x(t) = X(t) + x'(t) \quad (7)$$

into large scale slowly varying  $X(t)$  and small scale fluctuations  $x'(t)$  was realized with a simple symmetric running mean. Fluctuations  $x'(t)$  were obtained by subtracting that mean from the original signal. Unless specified otherwise, the chosen window was 50 s which corresponds to the distance of  $\sim 1 \text{ km}$ . Such length is enough to penetrate at least a few large turbulent eddies typical for the atmospheric boundary layer (Malinowski et al., 2013).

#### 4.1 Turbulence Kinetic Energy and variances

Variances of turbulent fluctuations  $\langle u'^2 \rangle$ ,  $\langle w'^2 \rangle$ ,  $\langle T'^2 \rangle$ ,  $\langle q_v'^2 \rangle$  and third moment of vertical velocity fluctuations  $\langle w'^3 \rangle$  were obtained by taking the average along LEG, denoted as  $\langle \rangle$ . Because lateral wind fluctuations were not available, we assumed horizontal isotropy to approximate missing  $\langle v'^2 \rangle$  with  $\langle u'^2 \rangle$  in turbulence kinetic energy (TKE) calculation:

290 
$$\text{TKE} = \langle u'^2 \rangle + \frac{1}{2} \langle w'^2 \rangle. \quad (8)$$

~~Worth to remember~~, It is worth remembering that variances and TKE usually represent mostly large scales because larger eddies in turbulence cascade are more energetic than smaller ones.

The accuracy of the results is severely limited by the length of the LEGs. Based on the methods of Lenschow et al. (1994), in the boundary layer the variances are subject to the systematic sampling error of about 5 % and the random sampling error of about 20 %. In the case of  $\langle w'^3 \rangle$ , those errors are accordingly larger (order of 10 % and 100 %, respectively, unless  $\langle w'^3 \rangle$  is not very close to zero). Importantly, in the plots we provide the variability among subsegments which was found to be of the same order as the total sampling error, in most cases larger than it.

## 4.2 TKE production and heat fluxes

Turbulence kinetic energy can be generated by buoyancy and wind shear (ignoring advection and turbulent transport). We estimated two respective terms of the TKE budget equation (Stull, 1988), buoyancy production/consumption  $B$  and shear production  $S$ , employing eddy correlation:

$$B = \frac{g}{\langle \theta_v \rangle} \langle w' \theta'_v \rangle, \quad S = - \langle w' u' \rangle \frac{\partial u}{\partial z}. \quad (9)$$

Here, we could provide only longitudinal component of shear production because lateral wind fluctuations were not available. Correlations were computed along the LEGs. Derivatives were estimated from the PROFs covering the relevant altitude range. Inevitably, such an approach introduces some inaccuracy as the exact place and time of derivative estimation is different than for the correlation estimation. To quantify vertical transport of heat and moisture, we estimated sensible and latent heat fluxes according to:

$$Q_s = \rho c_p \langle w' \theta' \rangle, \quad Q_l = \rho L_v \langle w' q'_v \rangle \quad (10)$$

where  $\rho$  is air density.

~~Range~~ The range of scales represented in the correlations is limited by the ~~smaller among spatial resolutions of lowest spatial resolution of the~~ two multiplied signals. The anemometer ( $u, w, \theta_v$ ) resolves scales down to  $\sim 0.5$  m (where this limit stems from the path length and spectral transfer properties (Kaimal et al., 1968)), the thermometer ( $\theta$ ) down to  $\sim 2$  cm, the hygrometer ( $q_v$ ) down to  $\sim 1$  m. As a result,  $\langle w' \theta' \rangle$ ,  $\langle w' u' \rangle$  and  $\langle w' \theta' \rangle$  are resolved down to  $\sim 0.5$  m while  $\langle w' q'_v \rangle$  down to  $\sim 1$  m. Those three instruments work satisfactorily also inside clouds of moderate liquid water and droplet concentration, as our ~~SC-stratocumulus~~ (Cruette et al., 2000; Siebert and Teichmann, 2000). In comparison with some other studies, the buoyancy estimation in the cloud does not include the contributions of liquid water flux  $\langle w' q'_l \rangle$  and droplet sedimentation which are expected to be relatively small (considering moderate  $q_l$ ) and of opposite sign, therefore partly compensate.

Similarly to variances, the accuracy of the fluxes obtained with the method of eddy correlation is limited by the length of the LEGs. In the boundary layer, the systematic sampling error was estimated for about 5-10 % while the random sampling error for about 50 % (Lenschow et al., 1994), unless the flux does not vanish. The subsegment variability (marked with errorbars in the plots) is in most cases larger than the total sampling error.

Additionally,  $B$ ,  $Q_s$  and  $q_l$  at the surface were estimated with the Coupled Ocean–Atmosphere Response Experiment bulk algorithm in version 3.0 (COARE 3.0) described in Fairall et al. (2003). Sea surface temperature was taken from satellite multi-mission product provided by the Group for High Resolution Sea Surface Temperature (JPL MUR MEaSUREs Project, 2015) while all the other inputs were our measurements from the lowest point of the PROFs.

## 4.3 TKE dissipation rate

TKE dissipation rate  $\epsilon$  was calculated invoking common assumption of homogeneous, isotropic, stationary turbulence which leads to the specific form of power spectra and structure functions (Kolmogorov, 1941). Nevertheless, theoretical assumptions



are often hardly satisfied in the atmosphere, e.g. considering complex stratification, and therefore  $\epsilon$  estimation from moderate-  
 330 resolution (not directly resolving dissipative scales) measurements is challenging (Siebert et al., 2006b; Jen-La Plante et al.,  
 2016; Waclawczyk et al., 2017, 2020). To account for possible anisotropy,  $\epsilon$  was derived separately for longitudinal and vertical  
 velocity fluctuations, following the methods of Siebert et al. (2006b). We also characterized the quality of estimations with  
 additional parameters describing the deviation of experimental data from theoretical dependencies.

### 4.3.1 Structure function method

335 Second order structure function (~~SFCs~~SFC) was calculated for measured  $u'$  and  $w'$  according to the same equation:

$$D_u(r) = \langle |u'(x+r) - u'(x)|^2 \rangle \quad (11)$$

where  $r$  is distance between data points (given by ~~FA~~True air speed) and the average is taken over positions  $x$  along the  
 flight path. SFC was then resampled, i.e. averaged inside logarithmically equidistant bins covering the assumed inertial range  
 $r \in [0.4, 40]$  m, with eight bins per decade (see Fig. 7). The resampling was applied in order to account for the density of data  
 340 points increasing with scale in logarithmic coordinates.

Theory predicts that in the inertial range SFC has the form (Pope, 2000):

$$D(r) = C(\epsilon r)^{\frac{2}{3}} \quad (12)$$

where  $C$  is a constant, experimentally determined to  $C_u \approx 2.0$  for longitudinal and  $C_w \approx 2.6$  for ~~lateral-vertical~~ velocity  
 component. We calculated  $\epsilon^{sfc}$  by least squares fit of this relationship to the resampled SFC. Second fit was performed according  
 345 to:

$$D(r) = C^* r^s \quad (13)$$

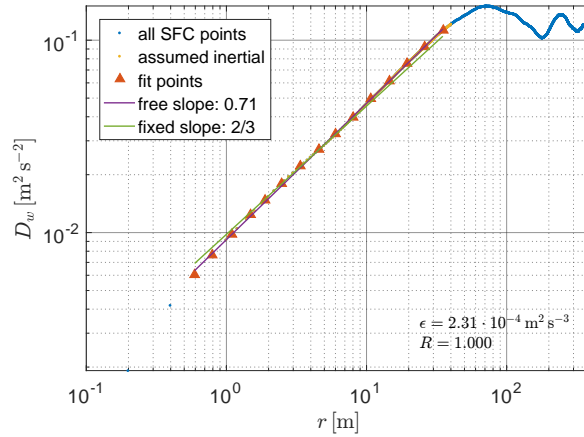
with two fitted parameters: prefactor  $C^*$  and exponent  $s$  corresponding to the slope in log-log plot. The exponent is used as  
 a benchmark of the agreement of the SFC form with theory. Additionally, Pearson correlation coefficient  $R^{sfc}$  was computed  
 for the resampled points. It quantifies the linearity of the experimental SFC in log-log coordinates. Consequently,  $s$  and  $R^{sfc}$   
 350 assess to some extent the reliability of derived  $\epsilon$ .

### 4.3.2 Power spectrum method

Power spectral density (PSD) of  $u'$  and  $w'$  was calculated with the Welch algorithm. The window was chosen as half the length  
 of the segment. The windows overlap by half of their length, so in turn there are three individual PSDs averaged in the Welch  
 scheme. PSD was resampled in the assumed inertial range, analogously to SFC (see Fig. 8).

355 Theory predicts the following PSD form in the inertial range (Pope, 2000):

$$P(f) = C' \left( \frac{U_s}{2\pi} \right)^{\frac{2}{3}} \epsilon^{\frac{2}{3}} f^{-\frac{5}{3}} \quad (14)$$



**Figure 7.** Example of  $\epsilon$  derivation with structure function method (flight #5, [LEGS LEG307](#), vertical component). Computed SFC (Eq. (11), blue) is resampled in the assumed inertial range (yellow) to obtain logarithmically spaced points (triangles) which are used for least squares fits: one with free slope (Eq. (13), purple), one with fixed theoretical slope (Eq. (12), green).

where  $f$  is frequency and  $C'$  is a constant ( $C'_u \approx 0.49$  for longitudinal and  $C'_w \approx 0.65$  for [lateral-vertical](#) component). We derived  $\epsilon^{psd}$  by fitting this relationship to the resampled PSD. Second fit was performed according to:

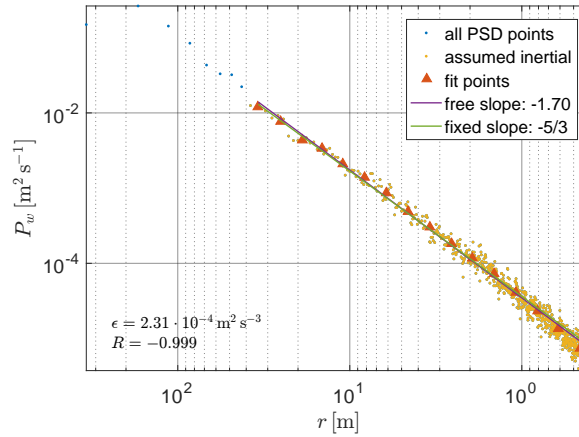
$$P(f) = C^* f^p \quad (15)$$

360 where fitted PSD exponent  $p$  corresponds to the slope in log-log plot. Together with Pearson correlation coefficient for the resampled points  $R^{psd}$  it measures the agreement of PSD form with theory and reliability of derived  $\epsilon$ .

### 4.3.3 Application of the methods

For PROFs, the moving window of 2 s was applied to the timeseries  $u'$  and  $w'$ . In each window,  $\epsilon$  was derived separately with the two methods, together with  $s$ ,  $R^{sfc}$ ,  $p$ ,  $R^{psd}$ . Such a solution was verified to provide sufficiently good fits and constitutes  
 365 the compromise between high final spatial resolution (short window desired) and adequate representation of SFC or PSD (long window desired). [Our approach follows earlier studies which determined the instantaneous dissipation rate utilizing the same type of data as ours \(Siebert et al., 2006b; Katzwinkel et al., 2012\). Siebert et al. \(2006b\) have chosen the window of 1 s based on their sensitivity tests and the arguments provided by Frehlich et al. \(2004\) and Muschinski et al. \(2004\). Because we derive not only  \$\epsilon\$  but also the slopes and correlations, we increased the window to 2 s so that the linear fit covers considerable portion](#)  
 370 [of the inertial range and the sufficient number of logarithmically equidistant resampled points \(see sec. 4.3.1\).](#)

In [the](#) case of LEGs, both methods were applied to the whole segment. Then, SFC and PSD were in practice averaged over relatively long horizontal distance. This approach provides an estimate of mean dissipation in contrast to local values computed in short windows which might differ from the mean (Kolmogorov, 1962). Also, SFC and PSD derived on long horizontal segment are expected to follow the theoretical form more accurately which is indeed the case.



**Figure 8.** Example of  $\epsilon$  derivation with power spectrum method (flight #5, [LEG5LEG307](#), vertical component). Computed PSD (blue) is resampled in the assumed inertial range (yellow) to obtain logarithmically spaced points (triangles) which are used for least squares fits: one with free slope (Eq. (15), purple), one with fixed theoretical slope (Eq. (14), green).

375 Our results (sec. 5.3) demonstrate a good agreement between the methods as long as relative variations with height are concerned. In terms of absolute values,  $\epsilon^{psd}$  is usually higher than  $\epsilon^{sfc}$  (around the factor of 2). In general, derived SFC resembles its theoretical form better than PSD which is indicated by the fitted exponents and correlation coefficients. This agrees with Siebert et al. (2006b) who found the SFC method to be more robust for  $\epsilon$  estimation from airborne platforms.

380 In order to estimate the uncertainties of the results, we used the random errors of the fitted parameters (computed with a standard method from least-squares fit residuals). The random error of ‘instantaneous’ (calculated in 2 s windows and serving for the derivation of the profiles) dissipation rate equals  $\sim 50\%$  in the boundary layer and  $\sim 150\%$  in the FT. The error of the LEG-derived  $\epsilon$  is  $\sim 30\%$  for longitudinal component and  $\sim 15\%$  for vertical component in the boundary layer while  $\sim 150\%$  for both components in the FT. The random error of the fitted slopes is  $\sim 0.04$  for  $s$  and  $\sim 0.16$  for  $p$  corresponding to the ‘instantaneous’ estimations while  $\sim 0.02$  in the case of both LEG-derived slopes. Notwithstanding, the given values represent  
 385 the uncertainties due to the random errors of the fit only. The reliability of the derived dissipation rates can be also assessed by comparing the results of the two derivation methods, by comparing the fitted SFC and PSD slopes with their theoretical values or using the deviation of the computed correlation coefficients from unity.

#### 4.4 Anisotropy

The assumption of isotropy might be violated in many specific situations in the atmospheric boundary layer, e.g. under strong  
 390 buoyancy and wind shear at [SC-stratocumulus](#) top (Malinowski et al., 2013; Jen-La Plante et al., 2016; Akinlabi et al., 2019). To investigate deviations from isotropy, we use anisotropy ratios  $A$  of two types, bulk and spectral, relating  $w$ -derived parameters to  $u$ -derived ones.

We define the following bulk anisotropy ratios:

$$A_2^{var} = \sqrt{\frac{\langle w'^2 \rangle}{\langle u'^2 \rangle}}, \quad A_\epsilon^{sfc} = \frac{\epsilon_w^{sfc}}{\epsilon_u^{sfc}}, \quad A_\epsilon^{psd} = \frac{\epsilon_w^{psd}}{\epsilon_u^{psd}}. \quad (16)$$

395 The first relates mostly to larger eddies which have dominant contribution to total variance. Isotropy is indicated by the values close to 1, while  $A_2^{var} < 1$  and  $A_2^{var} > 1$  indicate anisotropic turbulence dominated by horizontal and vertical fluctuations, respectively. On the other hand,  $A_\epsilon^{sfc}$  and  $A_\epsilon^{psd}$  regard mostly [the](#) inertial range eddies because  $\epsilon$  derivation exploits SFC or PSD scaling in [the](#) inertial range. Analogously, values close to unity indicate isotropy.

The spectral anisotropy is the scale-dependent ratio of PSDs for vertical and longitudinal velocity:

$$400 \quad A_P(r) = \frac{P_w(U_s/r)}{P_u(U_s/r)} \quad (17)$$

where [FAS-true air speed](#) is utilized to convert frequency into distance. [Similar-A similar](#) approach was exercised by Pedersen et al. (2018) who compared modeled and measured anisotropy in the region of [SE-stratocumulus](#) top. In [the](#) inertial range, Kolmogorov theory predicts  $A_P = 4/3$ . Such [value-of-a value of the](#) experimentally derived  $A_P(r)$  should then indicate isotropy at the particular scale  $r$ , [as in the analysis of Siebert and Muschinski \(2001\)](#). We applied the same resampling procedure as in  
405 sec. 4.3.2 to [the](#) LEG-derived PSDs but across the whole available range of scales (not only [the](#) inertial) and the ratio was then calculated point-by-point.

#### 4.5 [LengthscalesLength scales](#)

Turbulence energy cascade is often characterized by several [lengthscaleslength scales](#): integral scale  $L$ , Taylor microscale  $\lambda$  and Kolmogorov scale  $\eta$ . [Integral lengthscale corresponds to-The integral length scale corresponds to the](#) energy-containing eddies  
410 which are involved in TKE generation. In [the](#) energy cascade, it marks the beginning of [the](#) inertial subrange where turbulent flow is considerably isotropic despite the anisotropy of large scale factors. The indefinite integral of [the](#) autocorrelation function involved in [the](#) formal definition of  $L$  cannot be evaluated experimentally due to [the](#) limited length available. We estimated the distance where the autocorrelation

$$\rho_u(r) = \frac{\langle u'(x+r)u'(x) \rangle}{\langle u'^2 \rangle} \quad (18)$$

415 declines by a factor of  $e$ . This method is robust enough to provide reasonable results in all our cases. The very same procedure was applied to longitudinal as well as vertical velocity to provide  $L_u$  and  $L_w$ , respectively. According to Pope (2000), under isotropic conditions  $L_w = \frac{1}{2}L_u$ . Such [a](#) proportion can then indicate isotropy in [the](#) relevant large eddy scale.

At [the](#) Taylor microscale, viscosity starts to substantially affect the dynamics of turbulent eddies. Under [the](#) assumption of isotropy, it can be related to velocity variance and dissipation rate. We estimated two Taylor scales, longitudinal and vertical:

$$420 \quad \lambda_u = \sqrt{30\nu \frac{\langle u'^2 \rangle}{\epsilon_u^{sfc}}}, \quad \lambda_w = \sqrt{15\nu \frac{\langle w'^2 \rangle}{\epsilon_w^{sfc}}} \quad (19)$$

where  $\nu$  is air viscosity for which we accounted for temperature and pressure dependence (Sutherland, 1893). In homogeneous isotropic turbulence  $\lambda_w = \frac{1}{\sqrt{2}}\lambda_u$  (Pope, 2000).

Kolmogorov scale corresponds to [the](#) smallest eddies where TKE is dissipated into heat by viscosity. Following dimensional arguments of the famous similarity hypothesis, it equals:

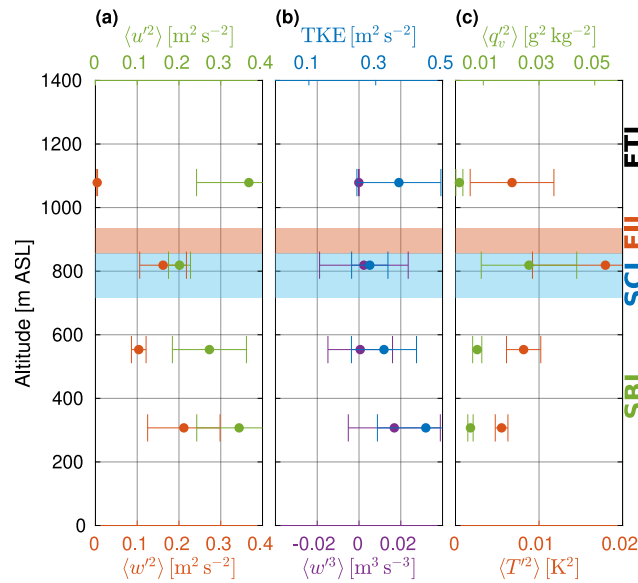
$$425 \quad \eta_u = \left( \frac{\nu^3}{\epsilon_u^{sfc}} \right)^{\frac{1}{4}}. \quad (20)$$

It was calculated separately for longitudinal ( $\eta_u$ ) and vertical ( $\eta_w$ ) direction with the same formula. Provided local small-scale isotropy, they should be equal. For convenience, in  $\lambda$  and  $\eta$  derivation, we used only  $\epsilon^{sfc}$  and neglected  $\epsilon^{psd}$  because SFC proved to resemble its theoretical form better (see sec. 5.3).

## 5 ~~Turbulence~~ Observed turbulence properties: results

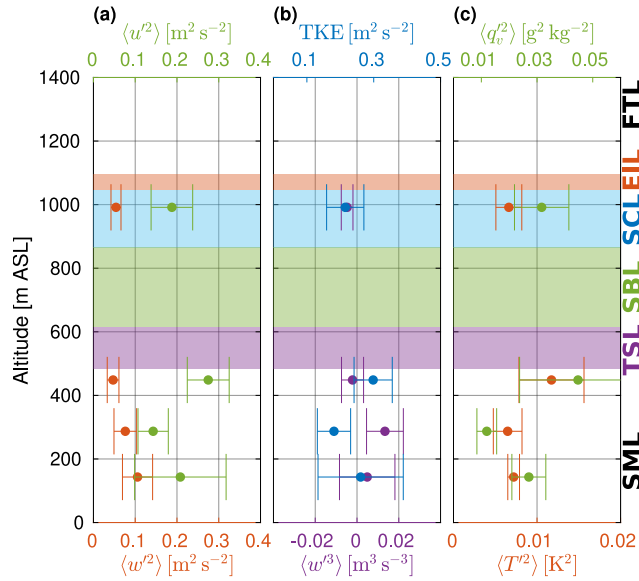
430 Turbulence properties in coupled and decoupled STBL are documented in a series of plots. ~~Depending on flight segment type, they are illustrated with continuous profiles (PROF) and/or dots with errorbars (LEG). For reference, the figures include the sublayer shading introduced in sec. 3.~~ Mean PROF-derived values inside the sublayers are listed in Tables A1 and A2.

### 5.1 Turbulence Kinetic Energy and variances



**Figure 9.** Statistics of turbulent fluctuations in the coupled STBL (flight #5): (a) variance of horizontal  $\langle w'^2 \rangle$  and vertical velocity  $\langle w'^2 \rangle$ , (b) turbulence kinetic energy TKE and third moment of vertical velocity  $\langle w'^3 \rangle$ , (c) variance of temperature  $\langle T'^2 \rangle$  and specific humidity  $\langle q_v'^2 \rangle$ .

Figs. 9 and 10 present variances of vertical and longitudinal velocity fluctuations, TKEs, third moments of vertical velocity, 435 variances of temperature and specific humidity in the LEGs of flight #5 and #14, respectively. Generally, the TKE inside the



**Figure 10.** As in Fig. 9 but for the decoupled STBL (flight #14).

coupled STBL decreases with height from the middle of the SBL up to the cloud top. Despite slightly unstable stratification, the contribution from horizontal velocity variance is dominant over the vertical one. The latter reaches a minimum value below the cloud, where the buoyancy production is close to zero (compare Fig.11 in the next section).

Estimated values of the TKE are also large in the FT above the temperature inversion. This is rather an artifact due to likely the presence of gravity waves favored under stable conditions (the power spectra of  $w$ ,  $u$ ,  $q_v$ ,  $\theta_v$  and the cospectra of  $wu$ ,  $wq_v$  and  $w\theta_v$  indicate the dominant contribution of the wavelength of about 450 m). Recall that LEG2-LEG1079 was flown very close to the EIL and the cloud top which often features undulated interface. Structure function, autocorrelation function as well as simple inspection of the velocity signal indicate oscillations of the wavelength of a few hundred meters.

The third moment of vertical velocity is positive in the lowest LEG at about 300 altitude LEG307, suggesting strong but localized updrafts and weak but widespread downdrafts. Higher up, it is close to zero. This results ought to be interpreted with caution because the estimation of  $\langle w'^3 \rangle$  can be subject to errors due to insufficient statistics related to the small chance of penetrating infrequent but intense events (Lenschow et al., 1994; Kopec et al., 2016).

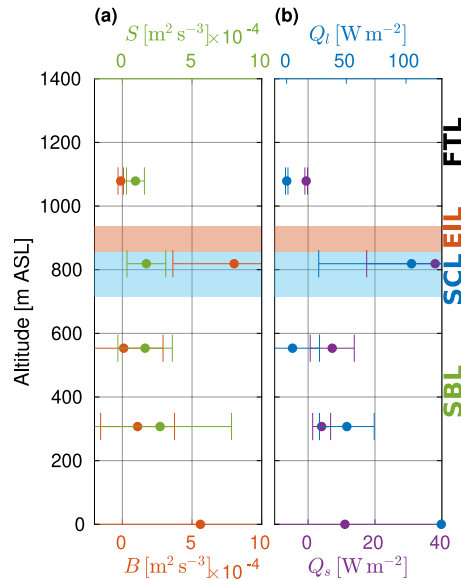
Fluctuations of temperature and humidity can be significant wherever there are spatial gradients of those quantities or in the presence of sources or sinks of heat and moisture. Such conditions occur close to the cloud top, where radiative cooling is the sink of heat and mixing between the air volumes of considerably contrasting properties occurs. Indeed, measured variances are highest in the cloud segment and decrease downward into the boundary layer where  $T$  and  $q_v$  are locally more uniform.

In the decoupled STBL, TKE level is in general lower than in the coupled case. The profiles of velocity variances across the SML resemble a typical mixed layer with shear, i.e. high TKE at the bottom and the top which is realized mostly by the

contribution of horizontal velocity variance (e.g., Stull, 1988, ch. 4). The prevalence of horizontal in comparison to vertical is particularly visible for LEG3LEG448, close to the transition, where the vertical velocity variance reaches its minimum. Similarly to TKE, humidity and temperature variances exhibit a maximum at this level.  $T$  and  $q_v$  can be considered passive scalars with no significant sources there. The TSL features the gradient of  $q_v$  (e.f. Fig. 6) which might explain increased local fluctuations, which undergo mixing. The increased variances are caused by gradient production (Term IV in the variance budget equations in the formulation of Stull (1988), his Eqs. (4.3.2) and (4.3.3)) rather than by any diabatic sources.

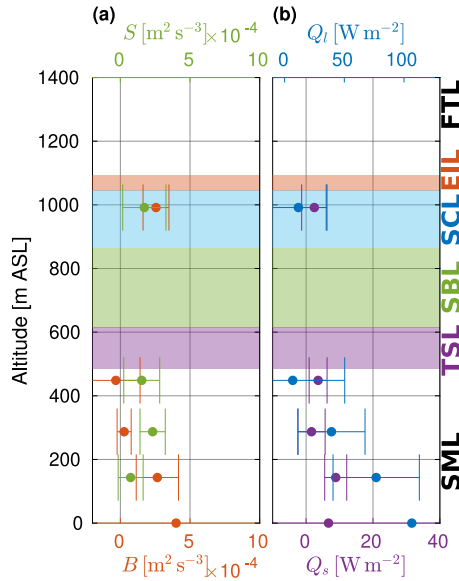
Skewness of vertical velocity is slightly positive in the SML with the maximum in LEG2LEG287. At the transition and in the cloud it is close to zero with tendency towards negative values. This suggests dominant role of updrafts in the SML and downdrafts in the SCL. Altogether, the results can be interpreted as a signature of decoupling between the circulations in lower and upper parts of the boundary layer, as downdrafts originated at cloud top and updrafts originated at the surface seem to slow down and diverge horizontally at the transition level.

## 5.2 TKE production and turbulent fluxes



**Figure 11.** (a) TKE production by buoyancy  $B$  and shear  $S$ , (b) sensible  $Q_s$  and latent  $Q_l$  heat fluxes in the coupled STBL (flight #5). The lowest dot denotes the parameterized surface value obtained with COARE 3.0 algorithm.

Buoyant production of TKE is expected to be significant inside the cloud and close to the surface while the shear production is expected to be significant at the bottom and at the top of the boundary layer (Markowski and Richardson, 2010). Such a picture is in general agreement with our results for flight #5. In the coupled STBL observed there (Fig. 11),  $B$  is maximum in the LEG flown inside the cloud ( $8.0 \cdot 10^{-4} \text{ m}^2 \text{ s}^{-3}$ ), drops to nearly zero below the cloud and increases towards the surface,



**Figure 12.** As in Fig. 11 but in the decoupled STBL (flight #14).

470 reaching  $5.6 \cdot 10^{-4} \text{ m}^2 \text{ s}^{-3}$  (estimated with COARE algorithm).  $S$  ~~appears to be~~ is more uniform in the boundary layer, yet subject to substantial variability among subsegments.

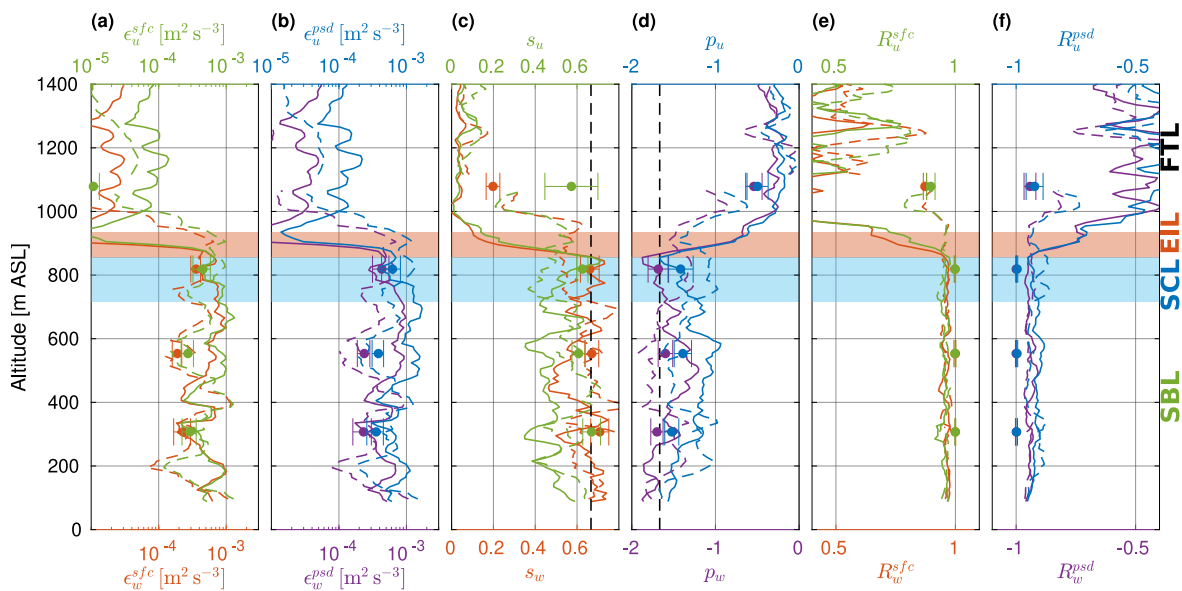
Sensible heat flux reaches maximum of almost  $40 \text{ W m}^{-2}$  close to the cloud top, stays small and positive in the middle of the boundary layer with the surface value of around  $Q_s = 11 \text{ W m}^{-2}$  (according to COARE parameterization). Latent heat flux ~~seems to follow~~ follows near linear decrease from  $Q_l = 130 \text{ W m}^{-2}$  at the ocean surface, which is the source of moisture due to  
 475 evaporation, to roughly zero below the cloud. At low levels in the atmosphere (at the surface and in LEG307) the contribution of moisture transport to buoyancy is of the same order as the contribution of heat transport (not shown). In the cloud top region ~~it~~  $Q_l$  exceeds  $100 \text{ W m}^{-2}$  (subject to very large variability). It is not clear what are the contributions of radiative and evaporative cooling towards the observed heat fluxes there. LEG3-LEG819 was performed close to the cloud top but neither exactly at the interface nor inside the EIL. Although CTEI-cloud top entrainment instability parameter  $\kappa$  significantly exceeds  
 480 the critical value (see sec. 3.2), which suggests the importance of evaporation, radiative cooling might still be dominant as in the study of Gerber et al. (2016).

In the decoupled STBL observed in flight #14 (Fig. 12), production terms are of the same order as in the coupled case. The COARE algorithm provides  $B = 4.0 \cdot 10^{-4} \text{ m}^2 \text{ s}^{-3}$ ,  $Q_s = 6.7 \text{ W m}^{-2}$ ,  $Q_l = 107 \text{ W m}^{-2}$  at the surface.  $B$  decreases with height turning into weak buoyancy consumption at the transition. This can be considered an important signature of decoupling.  
 485 Above, in the cloud,  $B$  is again positive, yet significantly smaller ( $2.6 \cdot 10^{-4} \text{ m}^2 \text{ s}^{-3}$ ) than at similar location in the coupled STBL. Shear production is present in the SML and at the transition as well as in the cloud top region.



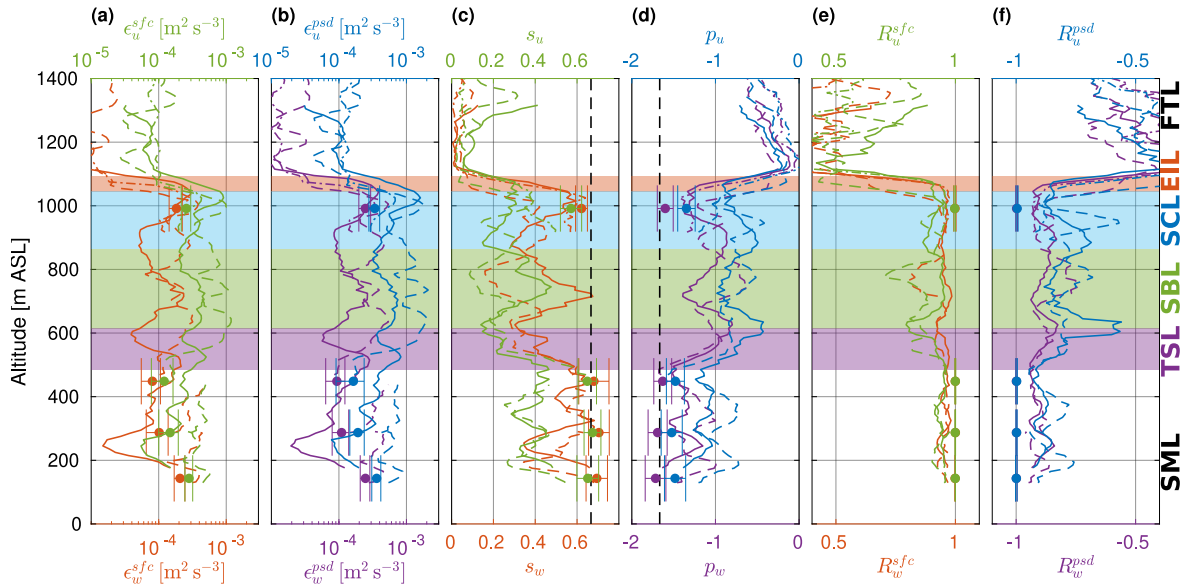
Sensible heat flux in the decoupled boundary layer is relatively small reaching maximum of  $\sim 10 \text{ W m}^{-2}$  at  $\sim 140 \text{ m}$ . Latent heat flux features near linear decrease with height from the maximum of  $\sim 100 \text{ W m}^{-2}$  at the surface to roughly zero at the transition. In the lower part of the STBL (at the surface, in LEG143 and LEG287) the contribution of moisture transport to buoyancy is of the same order as the contribution of heat transport (not shown). Both sensible and latent heat fluxes observed in the cloud (LEG5LEG992) are small, in contrast to the coupled case. ~~One may speculate~~ Together with rather moderate  $B$  in the cloud this suggests that the drivers of convection, i.e. radiative and evaporative cooling, are not as efficient in this situation which might have been one of the reasons why decoupling occurred. ~~This sounds consistent with rather moderate  $B$  in the cloud~~ The cloud top entrainment instability parameter  $\kappa$  (sec. 3.2) is indeed smaller in the decoupled cloud in comparison to the coupled one which implies less efficient evaporative cooling. However, the comparison of radiative cooling effects between the cases requires further investigation. Another observation is that the moisture delivery from the ocean surface to the cloud ~~might ought to~~ be more difficult in the decoupled STBL as  $Q_l$  vanishes at much lower height in relation to the cloud base than in the coupled case.

### 5.3 TKE dissipation rate



**Figure 13.** TKE dissipation rate and inertial range scaling in the coupled STBL (flight #5): (a), (b) dissipation rate  $\epsilon$ , (c), (d) fitted exponents  $s$  and  $p$ , (e), (f) correlation coefficient  $R$ . Superscripts  $sfc$  and  $psd$  denote the structure function and power spectrum methods, respectively. Subscripts  $u$  and  $w$  denote horizontal and vertical velocity components, respectively. Dissipation rates for LEG2-LEG1079 which are not visible in panels (a), (b) are smaller than  $10^{-5} \text{ m}^2 \text{ s}^{-3}$ .

500 Measurements in the coupled STBL during flight #5 (Fig. 13) indicate relatively small variability of TKE dissipation rate throughout the boundary layer depth and substantial decrease right above the cloud top. The values fluctuate by roughly



**Figure 14.** As in Fig. 13 but for the decoupled STBL (flight #14).

1 order of magnitude, between  $10^{-4} \text{ m}^2 \text{ s}^{-3}$  and  $10^{-3} \text{ m}^2 \text{ s}^{-3}$ . Importantly, those variations do not correlate between the PROFs, hence they are the manifestation of some intermittency and random effects involved in airborne sampling rather than any systematic stratification. Among the LEGs, the highest dissipation rate was observed in the one close to the cloud top, where also substantial buoyant production of TKE was revealed (see sec. 5.2). On the other hand, continuous profiles of  $\epsilon$  derived from PROFs do not show significant difference between the cloud and the subcloud part. It suggests that even though the TKE might be produced at specific places it is probably redistributed well by the circulation across the STBL before being dissipated by viscosity (c.f. transport analysis by Kopec et al. (2016)).

Inside the STBL, the exponents of structure function  $s$  (sec. 4.3.1) and of power spectra  $p$  (sec. 4.3.2) are close to their theoretical values ( $2/3$  and  $-5/3$ , respectively), in striking contrast to the FT. Individual deviations occasionally reach 40 % in the STBL. On average, the deviations are a bit smaller inside the SCL than in the SBL (see Table A1). Typically, SFCs and PSDs seem to be flatter than the theory predicts (absolute values of  $s$  and  $p$  smaller than theoretical). Such behavior might be attributed to the non-homogeneity and non-stationarity of turbulence and different stages of its development, e.g. decay (Vassilicos, 2015). When different velocity components are concerned, SFCs and PSDs of vertical fluctuations follow Kolmogorov theory closer than the longitudinal, signaling some anisotropy in turbulence energy cascade.

Correlation coefficients  $R^{sfc}$  and  $R^{psd}$  (sec. 4.3) are close to unity in the coupled STBL. This implies both the SFC and the PSD can be considered linear in log-log coordinates in the assumed inertial range of scales. The correlation is higher for LEGs than for PROFs due to better averaging. It sharply decreases across the EIL, suggesting that in the FT the assumptions involved in the derivation of  $\epsilon$  are not satisfied. Therefore,  $\epsilon$  estimates above the boundary layer cannot be considered credible

520 (Akinlabi et al., 2019). On the other hand, inside the STBL the observed forms of SFC and PSD are reasonably consistent with theoretical predictions.

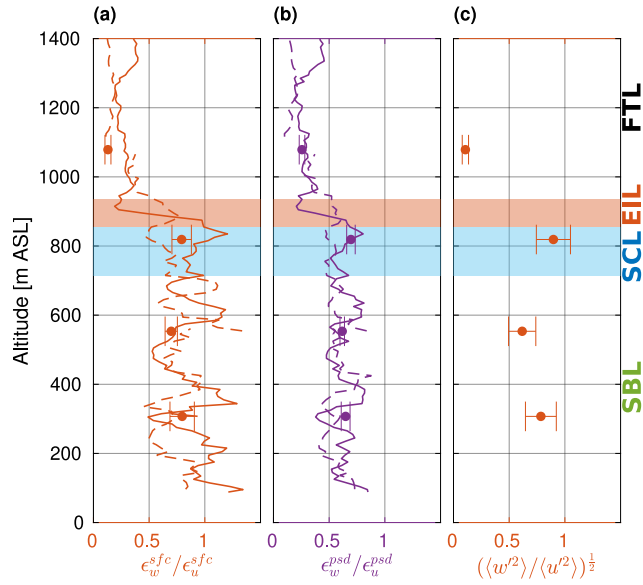
Measurements in the decoupled STBL during flight #14 (Fig. 14) present lower values of  $\epsilon$  and more variability with respect to height. PROF-derived results averaged across the sublayers increase from the SML up to the SCL (see Table A2). Such a trend is consistent for all derivation methods and velocity components, despite differences in the absolute values among them.  
525 The LEG-derived  $\epsilon$  decreases with height, from the surface up to the transition.

Vertical profiles of the fitted exponents  $s$  and  $p$  reveal internal layering of the STBL. In contrast to the coupled case, all PROF-derived exponents deviate significantly from theoretical values. The deviations are appreciably smaller in the SML than in the SBL and the SCL, clearly demonstrating that turbulence in the upper part of decoupled STBL is further from Kolmogorov's concepts than in the lower part. The parameters inside the SCL and the SBL are comparable, suggesting there is an efficient  
530 circulation and mixing across them. Those facts were expected, taking into account our analysis of stratification (sec. 3.4) and TKE production (sec. 5.2). Most probably, turbulence generated in the cloud top region is redistributed by the large eddies and the transport terms of the TKE balance equation (Stull, 1988) across the SCL and the SBL. Though, the properties of such turbulence are remarkably far from the Kolmogorov theory assuming homogeneity, isotropy and stationarity. In the light of this observation, the dissipation rates obtained with the methods based on the theoretical inertial range scalings can become  
535 questionable. The assumptions are better resembled by the conditions in the lowermost part of the atmosphere, albeit they are still distant from being exactly fulfilled. The profiles of  $R^{sfc}$  and  $R^{psd}$  are in agreement with the above hypothesis suggesting different character and origin of turbulence in the upper and lower part of the STBL. The absolute values are smaller than in the coupled case. In the SBL and the SCL the correlation is even quite poor at some particular heights.

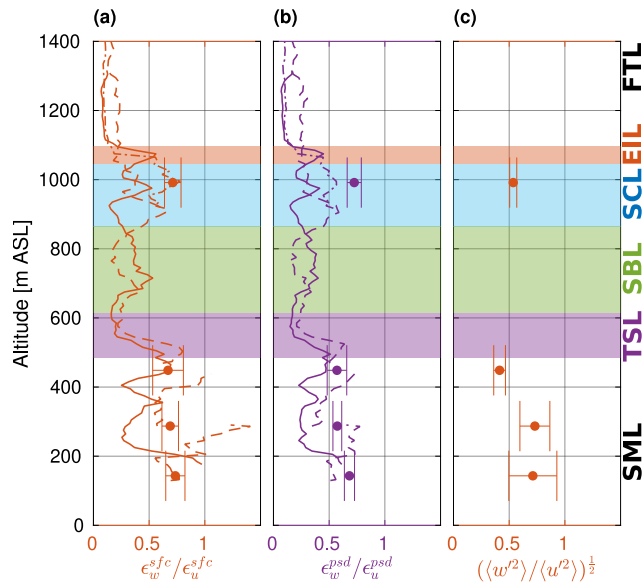
In contrast to the PROFs, the LEG-derived exponents stay mostly close to  $2/3$  or  $-5/3$ , accordingly, while the correlations are close to one. We suppose that the observed discrepancy results from the combination of horizontal inhomogeneity and intermittency of turbulence. PROF-derived and LEG-derived parameters should not be directly compared because they represent small and large fluid volumes, respectively. Unfortunately, none of the horizontal segments was performed in the SBL.

#### 5.4 Anisotropy

545 The coupled STBL sampled in flight #5 features bulk anisotropy ratios predominantly in the range between 0.5 and 1.0 (Fig. 15). The variance anisotropy is-ratio is the largest (0.9) for the horizontal segment inside the cloud, close to its top where the turbulence is efficiently generated by buoyancy (sec. 5.2). In the SBL the values are a bit smaller. Despite substantial local fluctuations observed in  $A_{\epsilon}^{sfc}$  and  $A_{\epsilon}^{psd}$ , their average level can be considered constant across the boundary layer. There is very little difference between the SBL and the SCL. The SFC-derived anisotropy ratio is relatively close to unity, suggesting  
550 near isotropic conditions. However, the PSD-derived ratio, typically around 0.6, seems to indicate the dominant role of horizontal fluctuations. The reason for such a discrepancy between the methods is not clear. It can be related to the bias in the estimation of dissipation rates between them (c.f. Waclawczyk et al., 2020). Nevertheless, both anisotropy measures indicate



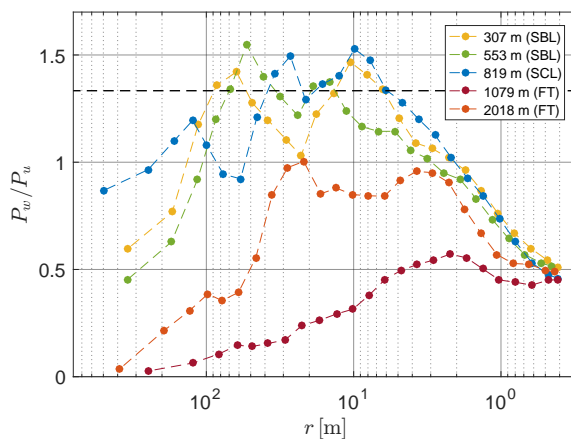
**Figure 15.** Anisotropy ratios in the coupled STBL (flight #5).



**Figure 16.** Anisotropy ratios in the decoupled STBL (flight #14).

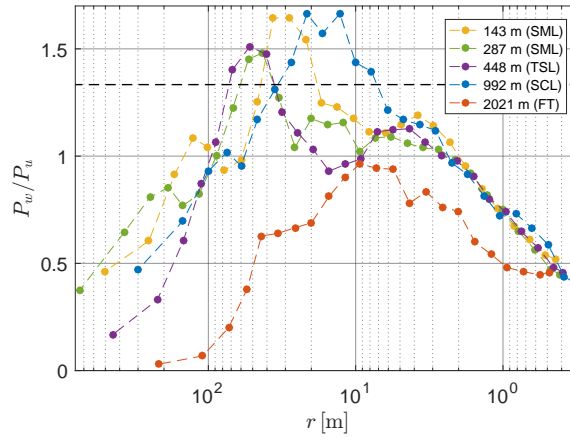
no internal layering inside the STBL. In the FT, under static stability and weak turbulence production, horizontal motions dominate.

555 In the decoupled STBL investigated in flight #14, bulk anisotropy ratios are on average smaller than in the previous case (Fig. 16), signaling prevalence of horizontal fluctuations over vertical ones.  $A_2^{var}$  is the largest in the surface layer (reaching 0.72), smaller in the cloud (0.54) and close to the transition (0.41) between the two circulation systems, cloud-driven and surface-driven. Dissipation-derived anisotropy ratios imply the separation of the STBL into two parts with the border in the TSL. In the upper part, covering the SCL and the SBL,  $A_\epsilon^{sfc}$  and  $A_\epsilon^{psd}$  are visibly smaller than in the SML. Again, the PSD-  
 560 derived rate is systematically lower than the SFC-derived, but the discrepancy is not as pronounced as in the case of flight #5. Importantly, the change at  $\sim 500$  m correlates well with the change in the fitted SFC and PSD exponents (see sec. 5.3) as well as with the gradient of specific humidity (see sec. 3.4). This fact confirms the hypothesis involving two major circulation circuits dividing the STBL into two parts which are internally relatively well-mixed but feature turbulence of different character. In the SML, turbulence seems to be more vigorous and isotropic than in the SCL and the SBL.



**Figure 17.** Spectral anisotropy ratio in the coupled STBL (flight #5). ~~LEG-derived curves are labeled according to the altitude.~~ The horizontal ~~dotted-dashed~~ line denotes the 4/3 level expected for isotropy in ~~the~~ inertial range.

565 Spectral anisotropy ratios in the coupled STBL presented in Fig. 17 are of similar form for all three LEGs inside the boundary layer, contrasting with those performed in the FT. Inside the STBL,  $A_P$  matches approximately the theoretical value of 4/3 in the range of 5-100 m, indicating isotropic properties of turbulence in the inertial subrange of the energy cascade. The anisotropy ratios gradually decreases for larger scales which are of the order of the integral lengthscale (see sec. 5.5). ~~Wavelengths~~ ~~The scales~~ of the size of a few hundred meters, which is close to the boundary layer depth (about 850 m), might  
 570 be additionally influenced by the proximity of the bottom and top interfaces limiting their vertical extent. On the opposite side of the spectrum (~~short wavelengths~~ ~~small scales~~),  $A_P$  can be affected by the differences in the spectral transfer functions of the sonic anemometer for different velocity components (Kaimal et al., 1968). Similar effect was briefly described by Siebert et al. (2006b). In the FT,  $A_P$  hardly reaches 1.0 because vertical excursions are damped by stability. In case of ~~LEG2~~ ~~LEG1079~~, it is particularly small, probably because that level was very close to the ~~immensely strongly~~ stable temperature inversion.



**Figure 18.** As in Fig. 17 but for the decoupled STBL (flight #14).

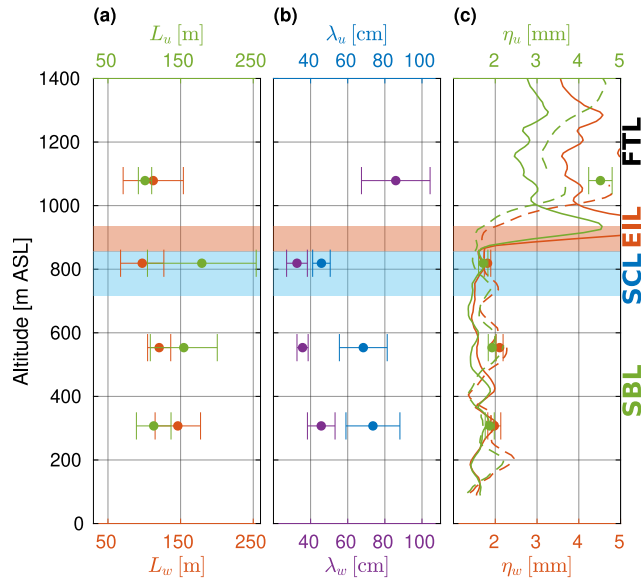
575 In the decoupled STBL sampled in flight #14 (Fig. 18),  $A_P$  follows similar pattern as observed in flight #5. Nonetheless, maximum values are higher, reaching up to 1.7 at the scale of 20-40 m in [LEG1 and LEG5](#) [LEG143 and LEG992](#) which are the lowest and highest segment inside STBL. One may speculate those scales, featuring prevalence of vertical fluctuations, are related to the typical size of surface layer plumes and to the typical size of cloud top downdrafts manifested as cloud holes (Gerber et al., 2005). The range of scales where  $A_P$  indicates conditions close to local isotropy is narrower than in the coupled

580 STBL. On the side of large scales,  $A_P$  falls below the theoretical 4/3 already at around 70 m for the two central LEGs and at around 50 m for the two peripheral LEGs (regarding the perspective of the STBL). This observation can be related to the integral [lengthscales](#) [length scales](#) which are smaller than in flight #5 for the most part (see sec. 5.5). What is more, the depths of the two sections of the boundary layer corresponding to the supposed circulation circuits ( $\sim 500$  m) are also smaller than the total depth of the coupled STBL ( $\sim 850$  m).

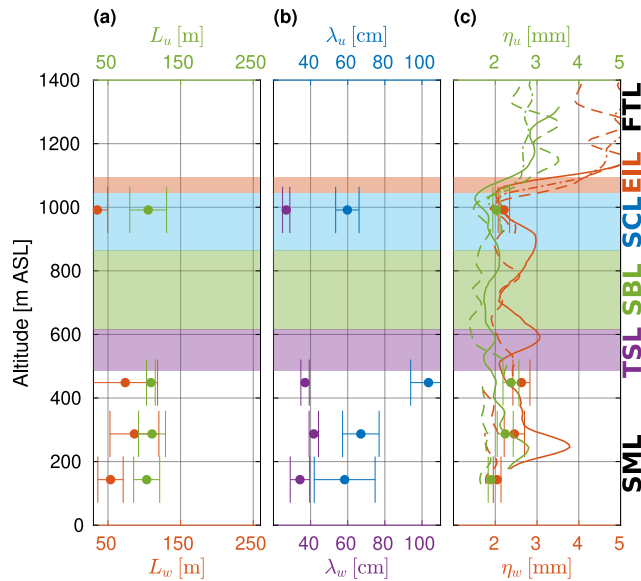
## 585 5.5 [Lengthscales](#) [Length scales](#)

In the coupled STBL, the estimated integral scales vary around 100-150 m (Fig. 19). The longitudinal scale  $L_u$  increases, whereas the vertical  $L_w$  decreases with height. The ratio  $L_w/L_u$  decreases from about 1.3 in the lowest LEG to about 0.5 (as expected for isotropic turbulence) close to the cloud top. The variability of integral scales among the subsegments of the LEGs is extensive, reflecting poor averaging on relatively short distances which prevents accurate calculation of decorrelation length.

590 Estimated Taylor microscales fit into the range of 30-80 cm and decline with height from the middle to the top of the STBL. As predicted, the longitudinal  $\lambda_u$  are larger than the vertical  $\lambda_w$ . Their ratio  $\lambda_u/\lambda_w$   $\lambda_u/\lambda_w$  equals  $\sqrt{2}$  (corresponding to isotropy of small-scale turbulence) only in the cloud LEG and is larger below. We may speculate that the turbulence is close to isotropic at the time and location of generation but such isotropy [might be is](#) broken in the process of transport. Kolmogorov microscale is almost constant across the STBL ( $\sim 2$  mm) which can be expected as it depends practically only on the dissipation rate (the



**Figure 19.** Turbulent lengthscaleslength scales in the coupled STBL (flight #5): (a) integral scale  $L$ , (b) Taylor microscale  $\lambda$ , (c) Kolmogorov scale  $\eta$ . Subscripts  $u$  and  $w$  denote horizontal and vertical velocity components, respectively. Some of the results for LEG2-LEG1079 in the FT are out of the range presented.



**Figure 20.** As in Fig. 19 but for the decoupled STBL (flight #14).

595 viscosity changes only by a minor part in the lower atmosphere). There is also no major difference between the horizontal and vertical direction.

In the decoupled STBL, integral scales are significantly smaller in comparison to the previous case, hardly exceeding 100 m (Fig. 20). The longitudinal  $L_u$  dominates over the vertical  $L_w$ , probably due to the separation of the circulation into two circuits and weak static stability which both limit the vertical extent of eddies and promote horizontal elongation. In contrast to the  
600 coupled case, the ratio  $L_w/L_u$  equals about one half in the lowest LEG close to the surface which is, however, again the location of intensive TKE production.

Taylor microscale is mostly of the same order as in the former case. In the transition zone and in the cloud, substantial detachment between the longitudinal and the vertical can be observed.  $\lambda_w/\lambda_u \lambda_u/\lambda_w$  is significantly larger than expected for isotropic turbulence. This effect is most pronounced in LEG3-LEG448 close to the transition. We may speculate it might be  
605 the consequence of decaying turbulence – far from the production in the cloud and at the surface, the TKE is here dissipated and consumed by weak buoyant stability (sec. 5.2). Kolmogorov scale visibly fluctuates but on average stays close to constant across the STBL. In contrast to the coupled case, there is some difference between  $\eta_u$  and  $\eta_w$  which directly relates to  $A_\epsilon^{sfc}$  discussed in sec. 5.4.

## 6 Summary and discussion

610 Two cases of marine stratocumulus-topped boundary layer, coupled (**EPC**) and decoupled (**DCPD**), have been compared in terms of stratification and turbulence properties. The observations were performed in summer in the region of Eastern North Atlantic with the use of the helicopter-borne platform ACTOS. Its moderate true air speed in combination with closely collocated fast-response instruments provides high spatial resolution measurements of turbulent fluctuations of wind velocity, temperature and humidity. Similarities and differences between the two cases can be summarized as follows.

### 615 1. Stratification

#### **CP**

**C** Conserved variables,  $\theta_l$  and  $q_t$ , feature nearly constant profiles up to the capping inversion at  $\sim 850$  m. LCL can be considered consistent with cloud base height.

#### **DCP**

620 **D** Above the relatively well-mixed SML,  $\theta_l$  slowly increases with height up to the capping inversion at  $\sim 1050$  m, indicating weak stability. There is a significant gradient of  $q_t$  in the TSL. LCL is close to the observed CB in the SBL only. Decoupling of the STBL was detected according to simple thermodynamic criteria.

In both cases winds are moderate and appreciable wind shear is observed across the cloud top and the EIL.

### 2. TKE production



625

**CP**

**C** TKE is efficiently generated by buoyancy with simultaneous importance of in-cloud and surface processes. Buoyancy production follows typical STBL profile: decreases with height from the surface upwards, vanishes or turns slightly negative below cloud base, to be again substantial inside the cloud due to latent heat release and diabatic cooling.

630

**DCP**

**D** TKE is generated by buoyancy at the surface and  $B$  decreases with height to zero at the SML top, turning into buoyancy consumption in the TSL. In the cloud  $B$  is weaker than at the surface, about three times smaller than for the **CPcoupled case**. Buoyancy effects can be also deduced from spectral anisotropy in the uppermost and lowermost boundary layer LEGs which suggests dominance of vertical motions in scales of 10-40 m.

635

The contribution of shear to TKE production is not negligible in both cases. This result can be partly artifact because only the longitudinal term could be evaluated and due to inaccurate estimation of horizontal wind gradient involved in shear term.

### 3. Heat fluxes

640

In both cases latent heat flux qualitatively resembles the profile of  $B$  which ~~suggests important~~ is consistent with the considerable contribution of moisture to buoyancy transport to buoyancy in the lower part of the STBL.  $Q_l$  is large at the ocean surface and decreases to zero at similar level as the minimum of  $B$ . Sensible heat flux is positive throughout observed layers but mostly smaller than  $Q_l$ .

**CP**

645

**C**  $Q_l$  and  $Q_s$  are positive and of significant magnitude close to the cloud top which can be attributed to diabatic cooling (radiative and/or evaporative).

**DCP**

**D**  $Q_l$  and  $Q_s$  are small close to the cloud top, about an order of magnitude weaker than for the **CPcoupled STBL**. Additionally,  $Q_l$  vanishes at ~~the a~~ level much lower in relation to the cloud base which might disturb moisture delivery from the ocean to the **SEstratocumulus cloud**.

650

### 4. Turbulent fluctuations

In both cases TKE is dominated by the contribution of horizontal velocity fluctuations. Variances of temperature and humidity are significant in the regions where mixing between air volumes of different properties occurs – due to local gradients or sources/sinks, i.e. at the cloud top, at the surface and at the transition in the **DCPdecoupled STBL**.

**CP**

655 **C** Maximum TKE is found in the middle of the SBL which together with positive  $\langle w'^3 \rangle$  at this level point out the role of surface-related factors in generating convection. ~~Vertical~~The vertical velocity variance suggests ~~the a~~ profile somewhat different than the convective similarity scaling. In cloud,  $\langle u'^2 \rangle$  and  $\langle w'^2 \rangle$  are almost equal implying isotropic conditions.

### **DCP**

660 **D** The SML follows the structure of a typical mixed layer with shear (c.f Stull, 1988). Updrafts are stronger than downdrafts. TKE,  $\langle T'^2 \rangle$  and  $\langle q_v'^2 \rangle$  are largest close to the transition. In cloud, fluctuations are relatively weak, in particular  $\langle w'^2 \rangle$ , in concordance with limited  $B$  and small heat fluxes.

## 5. TKE dissipation

### **CP**

665 **C** Derived  $\epsilon$  varies weakly throughout the height, i.e. despite accidental variations no systematic layering can be observed. Although TKE is efficiently produced by buoyancy in the cloud and at the surface, it is probably re-distributed well across the depth before being dissipated by viscosity. The form of SFCs and PSDs is reasonably consistent with theoretical predictions for inertial range scaling in homogeneous, isotropic, stationary turbulence (Kolmogorov, 1941). Though, less steep scaling (smaller absolute values of  $s$  and  $p$ ) can be found at some places  
670 in the SBL.

### **DCP**

**D** Derived  $\epsilon$  is smaller than in the CPcoupled case and features differences between the sublayers. Despite relatively high  $B$  at the surface, similar to the CPcoupled case, average  $\epsilon$  in the SML is smaller than in the SCL. Importantly, SFCs and PSDs scaling in the inertial range considerably deviates from the theoretical. Such behavior is characteristic for decaying turbulence (less energy than expected in large scales). These deviations are more pronounced and more variable in the SCL and SBL in comparison with the SML, underlining different character of turbulence  
675 in the upper and lower part of the DCPdecoupled STBL. Probably, TKE generated in the surface region and in the cloud, respectively, is redistributed in the two circulation zones separately, without major transport through the transition.

680 Discrepancies between PROF-derived and LEG-derived quantities result from the contrast between local and mean turbulence characteristics. The observed relative tendencies are consistent among derivation methods and velocity components, in spite of discrepancies in the absolute values.

## 6. Anisotropy of turbulence

### **CP**

685 **C** Derived anisotropy ratios indicate that turbulence is relatively close to isotropy. This condition is met best in the cloud where significant TKE production occurs.

## DCP

690 **D** The degree of anisotropy varies between the sublayers. In the uppermost part (SCL and SBL) horizontal small-scale velocity fluctuations dominate over the vertical. This effect is less pronounced in the SML. The change in anisotropy ratios in the TSL coincides with the difference in  $s$  and  $p$  right below the strong  $q_v$  gradient.

### 7. ~~Lengthscales~~ Length scales of turbulence

Integral ~~lengthscales~~ length scales of the order of 100 m show that turbulent eddies are substantially smaller than the depths of STBL or decoupled sublayers. Thus, they can be considered small enough to be transported by larger circulations.

695

## CP

**C** In the middle SBL,  $w'$  is correlated on longer distances than  $u'$ , while the opposite holds in the SCL. This agrees with the supposed form of circulation in the boundary layer, i.e. downdrafts originated at cloud top and updrafts originated at the surface pair in the middle and diverge horizontally in the vicinity of top and bottom boundaries.

## DCP ~~Integral lengthscales~~

700

**D** Integral length scales are smaller than in the CPcoupled case. In accordance with anisotropy ratios,  $L_u$  is larger than  $L_w$ . The same holds for Taylor microscales. The difference between  $\lambda_u$  and  $\lambda_w$  is particularly pronounced close to the transition. It seems that even smaller turbulent eddies there are elongated in horizontal.

Interestingly,  $L_w/L_u \approx \frac{1}{2}$  implied by isotropy assumption holds only in the regions of intensive buoyant TKE production: in the cloud for the CPcoupled STBL and close to the surface for the DCPdecoupled STBL. Kolmogorov scale is  
705  $\sim 2$  mm in both cases.

Most of our results concerning the coupled case are consistent with previous studies of SCstratocumulus dynamics (e.g. Nicholls and Turton, 1986; Duynkerke et al., 1995; Stevens et al., 2005; Kopec et al., 2016; Dodson and Small Griswold, 2021). In particular, the  $B$  profiles show that convection is driven both by cloud top cooling and by surface thermal instability. However, our results suggest the profile of  $\langle w'^2 \rangle$  being somewhat different than the convective similarity scaling (Lenschow  
710 et al., 1980) but rather having maximum in the cloud and minimum below it, with  $A_2^{var}$  following the same behavior, similarly to Dodson and Small Griswold (2021). Together with high TKE and positive  $\langle w'^3 \rangle$  in the middle SBL, this highlights the importance of surface process. It might be related to small cloud depth (relative to STBL depth) and net cooling at cloud top reduced during daytime in comparison to often considered nocturnal SCstratocumulus. In contrast to the works listed above, we do not clearly observe the maximum of  $\epsilon$  at the top and at the bottom of the STBL, but it is rather because others applied  
715 considerable horizontal averaging in comparison to local variability captured in our PROFs.

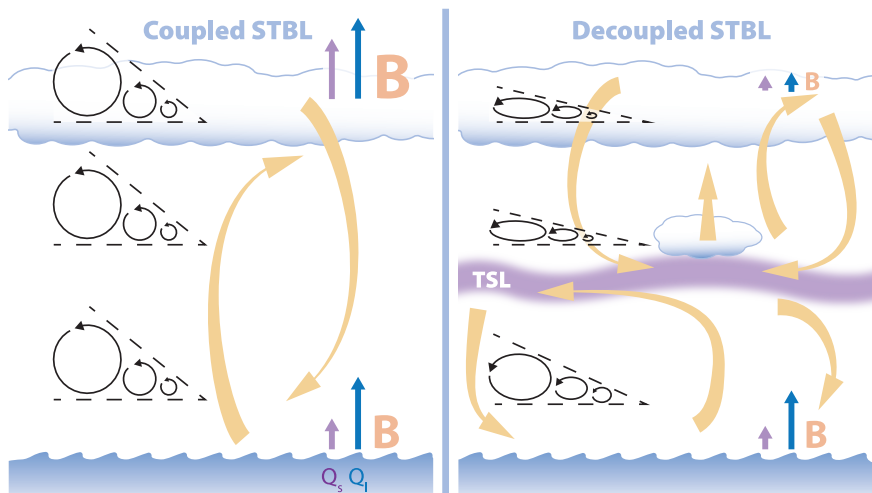
Our observations in the decoupled STBL summarized in points 1-4 fit well into the range of conditions reported in the literature, in particular the properties of the SML. Buoyant TKE production is positive in the cloud, while there is a region of negative  $B$  around the transition (Nicholls, 1984; Nicholls and Turton, 1986; Turton and Nicholls, 1987; Durand and Bourcy,

2001). Moreover,  $Q_l$  decreases from the surface to zero at the transition and it is substantially larger than  $Q_s$  in the SML  
720 (Nicholls, 1984; Tjernström and Rogers, 1996; De Roode and Duynkerke, 1997; Lambert and Durand, 1999; Durand and  
Bourcy, 2001). However, Lambert and Durand (1999) dispute the nearly linear character of this decrease, suggesting rather  
sharp gradient right at the SML top. Comparable to Nicholls (1984), our variances  $\langle T'^2 \rangle$ ,  $\langle q_v'^2 \rangle$  are significant close to the  
surface and have local minimum in the middle SML where in turn  $\langle w'^2 \rangle$  is relatively large. As in De Roode and Duynkerke  
(1997),  $\langle w'^3 \rangle$  is positive in the SML and nearly zero in the SCL, although the LEGs were rather too short to ensure statistical  
725 significance of those results. On the other hand, we did not collect enough data in the SCL and SBL to judge whether they  
together exhibit upside-down convective scaling as in Nicholls and Turton (1986); Tjernström and Rogers (1996); De Roode  
and Duynkerke (1997).

The results of our comparison between coupled and decoupled STBL are in agreement with the common concept of the  
dominant mixing patterns in such boundary layers (e.g. Wood, 2012). Decoupling occurs when the thermally driven circulation  
730 weakens to the level that it cannot mix air throughout entire depth. Then, STBL separates into two parts: cloud driven and  
surface driven. Explaining the particular mechanism of decoupling operating in our case is beyond the scope of this study and  
would require more complete data on air mass history. Nevertheless, "deepening-warming" mechanism (Bretherton and Wyant,  
1997) seems plausible. Such conclusion was reached by Kazemirad and Miller (2020) who modeled lagrangian evolution of  
STBL on synoptic scale in the period including our measurements. Deepening-warming is typical for the [ENA-region-region of](#)  
735 [the Eastern North Atlantic](#) where air masses are advected over progressively warmer waters. The most important driver for this  
process is the increasing ratio of surface latent heat flux to net radiative cooling in the cloud. The former was indeed relatively  
large, the latter was probably reduced by daytime solar heating. In addition, some precipitation was reported shortly before the  
flight and evaporative cooling could have contributed to stabilizing the lower STBL. Finally, decoupling occurs more readily  
for large entrainment efficiency. Derived  $B$  is weak in the cloud, much smaller than in the coupled one, which might be the  
740 result of enhanced entrainment warming offsetting radiative cooling (c.f. De Roode and Duynkerke, 1997).

The important novelty of our work are the results on small-scale turbulence (points 5-7 of the summary). As far as we know,  
local  $\epsilon$  profile, inertial range scaling exponents and anisotropy ratios were not addressed in the context of STBL coupling  
before. Based on the observations, we hypothesize that turbulence is redistributed across the depth of the [CP-coupled STBL](#)  
but in case of the [DCP-decoupled STBL](#) primarily in the sublayer where it was generated. Therefore, specific microscopic  
745 properties – TKE dissipation rate, inertial range scaling and anisotropy – can differ between the parts of the [DCPdecoupled](#)  
[STBL](#).

We consider it important to emphasize often omitted distinction between *circulation* and *turbulence*. By *circulation* we un-  
derstand motions responsible for mixing across relatively deep layers, of vertical scales comparable to [PBL-the boundary layer](#)  
depth. They usually originate from thermally driven plumes, sinking from cloud top or rising from the surface. Circulation  
750 might take form of organized structures of downdrafts and updrafts (resembling Rayleigh-Bennard convection cells). Those  
correspond to the peak in vertical velocity spectra, typically at  $\sim 1$  km in STBL (Lambert et al., 1999). *Turbulence* features  
cascade of eddies with universal scaling properties (Kolmogorov, 1941), spanning from the integral [lengthscale-length scale](#)  
( $\sim 100$  m in STBL) down to the Kolmogorov scale ( $\sim 1$  mm) where TKE is dissipated by viscosity. Such turbulence can be gen-



**Figure 21.** Schematic of main processes in the coupled (left) and decoupled (right) STBL: primary circulation (yellow arrows), turbulence eddy cascade (circular arrows confined in an angle with extent proportional to inertial range scaling exponent  $p$ ), TKE buoyancy production (red B letter of size proportional to strength), sensible and latent heat fluxes (purple and blue arrows, respectively, of length proportional to strength) at the surface and in the cloud top region.

755 erated by flow instabilities at specific locations (here typically close to the surface and cloud top) and distributed by circulation within STBL, alongside other constituents. Importantly, the variances and fluxes estimated in our study include contributions of both phenomena. Circulation is only partly resolved as we applied the cutoff of  $\sim 1$  km in Reynolds decomposition due to limited length of LEGs. Similar issue was also raised by De Roode and Duynkerke (1997). The advantage of our work is a good representation of turbulence because we resolve significant portion of the inertial range. ~~Main~~ The main processes operating in the coupled and decoupled STBLs, including circulation and turbulence, are schematically illustrated in Fig. 21.



**Figure 22.** Cumulus clouds under stratocumulus in the decoupled STBL. Photograph was taken during PROF5 of flight #14 by the camera mounted on the bottom of ACTOS.

760 Both turbulence and circulation can contribute to vertical transport of heat and moisture which is crucial for maintaining  
~~SC~~stratocumulus cloud. In the decoupled STBL, transport by turbulence through the transition is rather limited. However,  
we speculate it can be efficiently realized by a small number of updrafts which are strong and moist enough to penetrate  
the conditionally unstable TSL (measured  $\Gamma_T = -7.1 \text{ K km}^{-1}$ , moist adiabatic  $\Gamma_T = -4.7 \text{ K km}^{-1}$ ), reach their LCL and form  
cumulus clouds. The image of those cumuli was captured by a camera onboard ACTOS (Fig. 22). Based on the series of images  
765 from PROF5, we estimated the cloud base height  $\sim 660 \text{ m}$  (equal to mean LCL in the TSL) and cloud depth  $\sim 100 \text{ m}$ . None  
of those cumuli was penetrated by ACTOS, so it is not possible to distinguish dynamic effects responsible for their formation.  
Detailed analysis of vertical transport calls for high-resolution numerical simulations to be setup with the help of our results.

The onset of cumulus convection depends on the properties of the TSL which is then ~~imortant~~important for overall STBL  
dynamics. However, it is a challenge to conduct relevant ~~systematical~~systematic climatological analysis of TSL existence and  
770 ~~proprties~~properties due to limited number of observations. The reason is often insufficient resolution of routine radiosoundings.  
For instance, the layer of the strongest gradient in  $q_v$  (550-600 m) penetrated in PROF5 features the differences of  $\Delta\theta = 0.4 \text{ K}$ ,  
 $\Delta q_v = 1 \text{ g kg}^{-1}$  (equivalent to  $\Delta RH = 8 \%$ ) and  $\Delta LCL = 160 \text{ m}$ . With the ascent rate of  $\sim 5 \text{ m s}^{-1}$  and sampling interval  
of  $\sim 2 \text{ s}$ , a hygrometer with the time constant of a second and the accuracy of a single percent in RH would be desired.  
Moreover, TSL is not exactly flat but rather undulated as suggested by our data of ~~LEG3~~LEG448. Therefore, even aircraft  
775 measurements may fail to properly capture local conditions. This was pointed out already by (Turton and Nicholls, 1987, p.  
997) who underlined the role of good observation strategy: “While cloud layer decoupling is predicted to occur quite often,  
the consequential modification of the horizontally averaged vertical thermodynamic structure remains fairly small. (...) Data  
averaged in this way will appear ‘nearly well-mixed’ whether separation has occurred or not. A more detailed analysis of  
individual profiles and turbulence data is necessary to determine whether decoupling has taken place”.

780 *Data availability.* The whole dataset collected within the ACORES field project is planned to be archived on the PANGEA server for public  
access. The data used in the present study is also available from the authors upon request.

*Author contributions.* All the authors participated in the instrument preparation, measurements and data postprocessing within the ACORES  
project where H.S. was the principal investigator. J.L.N. designed the presented analysis with advice from S.P.M and H.S. The analysis was  
performed by J.L.N. with contributions from K.E.S. and with guidance of H.S. and S.P.M. J.L.N. wrote the manuscript with contributions  
785 from S.P.M. and H.S.

*Competing interests.* The authors declare that they have no conflict of interest.

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## **Appendix A: Average conditions in the sublayers**

Average meteorological parameters and turbulence properties inside the sublayers of the atmosphere are summarized in Tables A1 and A2 for the coupled (flight #5) and decoupled (flight #14) case, respectively. The selection of the sublayers is explained in sec. 3. The average values were obtained from the data of the same PROF which served for sublayer selection, i.e. PROF1 in coupled case, PROF5 in decoupled case.  $\Gamma_T$ ,  $Nb^2$  and  $Sh^2$  were calculated by estimating derivatives over sublayer depth. Other parameters were simply averaged in the relevant altitude range.

**Table A1.** Average conditions inside the sublayers in the case of coupled STBL (flight #5).

<b>Parameter</b>	<b>SBL</b> Subcloud layer	<b>SCL</b> Strato- cumulus layer	<b>EIL</b> Entrainment interface layer	<b>FTL</b> Free tropo- spheric layer
Height [m]	0 - 715	715 - 855	855 - 935	1005 - 1385
$T$ [° C]	16.24	12.59	14.53	14.41
$\theta_i$ [° C]	17.62	17.52	20.59	23.54
$\Gamma_T$ [K km <sup>-1</sup> ]	-10.9	-10.1	73.9	-7.2
$q_t$ [g kg <sup>-1</sup> ]	9.53	9.43	3.19	3.89
$U$ [m s <sup>-1</sup> ]	5.3	5.0	6.5	6.8
$dd$ [°]	337	330	329	323
LCL [m]	814	845	3363	3130
Nb <sup>2</sup> [10 <sup>-4</sup> s <sup>-2</sup> ]	-0.4	-0.6	15.4	0.7
Sh <sup>2</sup> [10 <sup>-4</sup> s <sup>-2</sup> ]	0.0	0.3	5.1	1.0
$\epsilon_w^{sfc}$ [10 <sup>-4</sup> m <sup>2</sup> s <sup>-3</sup> ]	5.6	6.1	1.9	0.2
$\epsilon_u^{sfc}$ [10 <sup>-4</sup> m <sup>2</sup> s <sup>-3</sup> ]	6.5	6.6	2.2	0.8
$\epsilon_w^{psd}$ [10 <sup>-4</sup> m <sup>2</sup> s <sup>-3</sup> ]	5.6	5.1	1.5	0.3
$\epsilon_u^{psd}$ [10 <sup>-4</sup> m <sup>2</sup> s <sup>-3</sup> ]	9.2	8.5	2.6	1.2
$s_w$	0.61	0.67	0.29	0.03
$s_u$	0.47	0.55	0.34	0.05
$p_w$	-1.53	-1.70	-1.10	-0.31
$p_u$	-1.25	-1.42	-1.03	-0.23
$R_w^{sfc}$	0.96	0.97	0.79	0.37
$R_u^{sfc}$	0.95	0.96	0.87	0.42
$R_w^{psd}$	-0.94	-0.95	-0.81	-0.49
$R_u^{psd}$	-0.91	-0.93	-0.81	-0.41
$\epsilon_w^{sfc}/\epsilon_u^{sfc}$	0.87	0.94	0.54	0.28
$\epsilon_w^{psd}/\epsilon_u^{psd}$	0.62	0.63	0.41	0.29
$\eta_w^{sfc}$ [mm]	1.7	1.6	4.0	4.0
$\eta_u^{sfc}$ [mm]	1.6	1.6	3.0	2.9



**Table A2.** Average conditions inside the sublayers in the case of decoupled STBL (flight #14).

<b>Parameter</b>	<b>SML</b> Surface mixed layer	<b>TSL</b> Transition layer	<b>SBL</b> Subcloud layer	<b>SCL</b> Strato- cumulus layer	<b>EIL</b> Entrainment interface layer	<b>FTL</b> Free tropo- spheric layer
Height [m]	0 - 385	485 - 615	615 - 865	865 - 1045	1045 - 1095	1150 - 1400
$T$ [ $^{\circ}$ C]	18.06	15.79	14.36	13.10	13.90	16.05
$\theta_t$ [ $^{\circ}$ C]	18.81	19.20	19.61	20.16	22.37	26.29
$\Gamma_T$ [K km $^{-1}$ ]	-10.1	-7.1	-7.4	-2.9	84.6	-5.2
$q_t$ [g kg $^{-1}$ ]	11.65	11.08	10.75	10.68	9.65	8.48
$U$ [m s $^{-1}$ ]	6.5	5.8	5.5	6.0	7.3	9.9
$dd$ [ $^{\circ}$ ]	314	308	314	322	322	325
LCL [m]	508	658	769	905	1328	2040
Nb $^2$ [ $10^{-4}$ s $^{-2}$ ]	0.5	0.9	0.1	1.5	28.0	1.5
Sh $^2$ [ $10^{-4}$ s $^{-2}$ ]	0.2	0.8	0.1	0.1	45.6	1.5
$\epsilon_w^{sfc}$ [ $10^{-4}$ m $^2$ s $^{-3}$ ]	0.6	1.1	1.2	1.3	1.8	0.1
$\epsilon_u^{sfc}$ [ $10^{-4}$ m $^2$ s $^{-3}$ ]	1.2	3.4	3.5	4.6	3.8	0.6
$\epsilon_w^{psd}$ [ $10^{-4}$ m $^2$ s $^{-3}$ ]	0.6	1.5	1.6	1.9	2.5	0.1
$\epsilon_u^{psd}$ [ $10^{-4}$ m $^2$ s $^{-3}$ ]	1.9	5.6	5.4	7.8	6.5	0.9
$s_w$	0.52	0.45	0.47	0.44	0.38	0.04
$s_u$	0.38	0.27	0.33	0.24	0.28	0.16
$p_w$	-1.39	-1.10	-1.10	-1.11	-1.05	-0.34
$p_u$	-1.16	-0.76	-0.78	-0.68	-0.85	-0.46
$R_w^{sfc}$	0.95	0.96	0.96	0.96	0.87	0.30
$R_u^{sfc}$	0.94	0.91	0.92	0.90	0.89	0.70
$R_w^{psd}$	-0.90	-0.89	-0.89	-0.89	-0.81	-0.45
$R_u^{psd}$	-0.89	-0.79	-0.79	-0.79	-0.83	-0.59
$\epsilon_w^{sfc}/\epsilon_u^{sfc}$	0.48	0.31	0.34	0.29	0.48	0.09
$\epsilon_w^{psd}/\epsilon_u^{psd}$	0.34	0.26	0.30	0.24	0.39	0.09
$\eta_w^{sfc}$ [mm]	3.0	2.6	2.5	2.5	2.4	5.6
$\eta_u^{sfc}$ [mm]	2.4	1.9	1.9	1.8	1.9	3.0

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