Authors' Response to the Anonymous Referee #1

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We are grateful to the Referee #1 for the insightful comments and suggestions on our manuscript. We respond to them in detail below. The original review is given in black, our anwers in blue. The responses also mention the specific corrections which were applied to the manuscript.

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 overrunnig 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 classs 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 lenghts. 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 $\mathrm{m\,s^{-1}}$ 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 $\mathrm{m\,s^{-1}}$ and TAS ~20 $\mathrm{m\,s^{-1}}$. The horizontal component of motion is necessary to avoid the downwash of the helicopter affecting wind and turbulence measurements on ACTOS.

Table 1. Mean altitude and length of the LEGs.

Flight #5	**LEG5**	**LEG4**	**LEG3**	**LEG2**	**LEG1**
Height [m]	307	553	819	1079	2018
Length [km]	5.44	5.51	7.93	3.94	6.25
Flight #14	**LEG1**	**LEG2**	**LEG3**	**LEG5**	**LEG4**
Height [m]	143	287	448	992	2021
Length [km]	8.11	11.92	7.10	4.79	3.49

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.

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., 2006) 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. (2006).

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, θ_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).
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> 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.

References

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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
θ'_v	L_{θ_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
θ_v'	L_{θ_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	
$\langle w'^2 \rangle$	$[\mathrm{m^2\,s^{-2}}, \%]$	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
$\langle w'^3 \rangle$	$[10^{-2}\mathrm{m^3\,s^{-3}}, \%]$	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
$\langle u'^2 \rangle$	$[\mathrm{m^2\,s^{-2}}, \%]$	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
$\langle q_v'^2 \rangle$	$[10^{-3}\mathrm{g^2\,kg^{-2}}, \%]$	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
$\langle T'^2 \rangle$	$[10^{-3}\mathrm{K^2}, \%]$	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	
$\langle w'^2 \rangle$	$[\mathrm{m^2\,s^{-2}}, \%]$	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
$\langle w'^3 \rangle$	$[10^{-2}\mathrm{m^3\,s^{-3}}, \%]$	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
$\langle u'^2 \rangle$	$[\mathrm{m^2\,s^{-2}}, \%]$	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
$\langle q_v'^2 \rangle$	$[10^{-3}\mathrm{g^2\,kg^{-2}}, \%]$	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
$\langle T'^2 \rangle$	$[10^{-3}\mathrm{K^2}, \%]$	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	$[10^{-4}\mathrm{m}^2\,\mathrm{s}^{-3}, \%]$	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	$[10^{-4}\mathrm{m}^2\,\mathrm{s}^{-3}, \%]$	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	$[\mathrm{W\,m}^{-2}, \%]$	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	$[\mathrm{W\,m}^{-2}, \%]$	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	
B	$[10^{-4}\mathrm{m}^2\,\mathrm{s}^{-3}, \%]$	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
S	$[10^{-4}\mathrm{m}^2\,\mathrm{s}^{-3}, \%]$	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
Q_s	$[\mathrm{W\,m}^{-2}, \%]$	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
Q_l	$[\mathrm{W\,m}^{-2}, \%]$	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