Aircraft observational constraints on stratocumulus entrainment

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J. K. Carman, D. L. Rossiter, D. Khelif, H. H. Jonsson, I. C. Faloona, and P. Y. Chuang, ACP, 2012

See also:

Gerber et al., Entrainment rates and microphysics in POST stratocumulus, JGR, 2013

Malinowski et al., Physics of Stratocumulus Top (POST): turbulent mixing across capping inversion, ACP, 2013

Entrainment in dry convective boundary layers

- Ball (1960).

$$\frac{entrainment\ flux}{surface\ flux} = -\frac{\overline{(\theta w)}_i}{\overline{(\theta w)}_0} = 0.04$$

- Zeman and Tennekes (1977) propose a parameterization that depends on stratification above the inversion:

$$-\frac{\overline{(\theta w)}_i}{\overline{(\theta w)}_0} = \frac{C_F - C_D \omega_B h / w_*}{1 + C_T {w_*}^2 T_0 / g h \Delta\Theta}. \qquad (24)$$

The ratio $\overline{(\theta w)}_i / \overline{(\theta w)}_0$ therefore is no longer constant; it depends on the stratification parameter $\omega_B h / w_*$ and

Entrainment in cloud-topped boundary layers

- Kraus and Schaller (1978) propose a parameterization based on the buoyancy flux ratio:

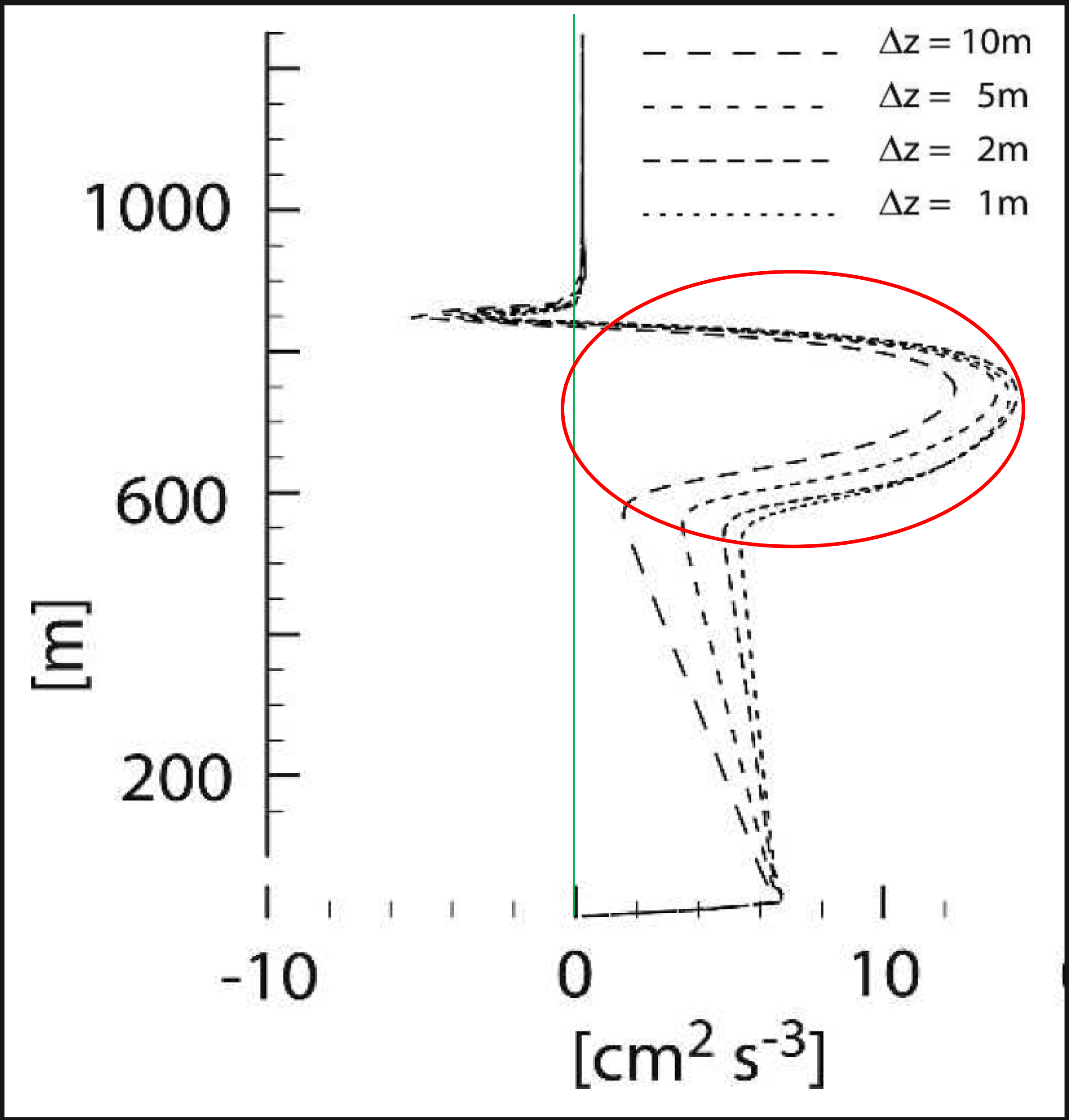
$$r = -\frac{\int_{p_b}^{p_s} (F_{sv} < 0)\,dp}{\int_{p_b}^{p_s} (F_{sv} > 0)\,dp} = \text{constant}$$

- Simulations from Deardorff 1980 show *r* values between 0.01 and 0.1.

- Nichols and Turton (1986) evaluated a number of parameterizations against observations. They found that Kraus and Schaller (1978) is most successful.

- This study: observations show that *r* depends on cloud top stratification.

Buoyancy flux profile in stratocumulus



Stevens et al., Mon. Wea. Rev., 2005

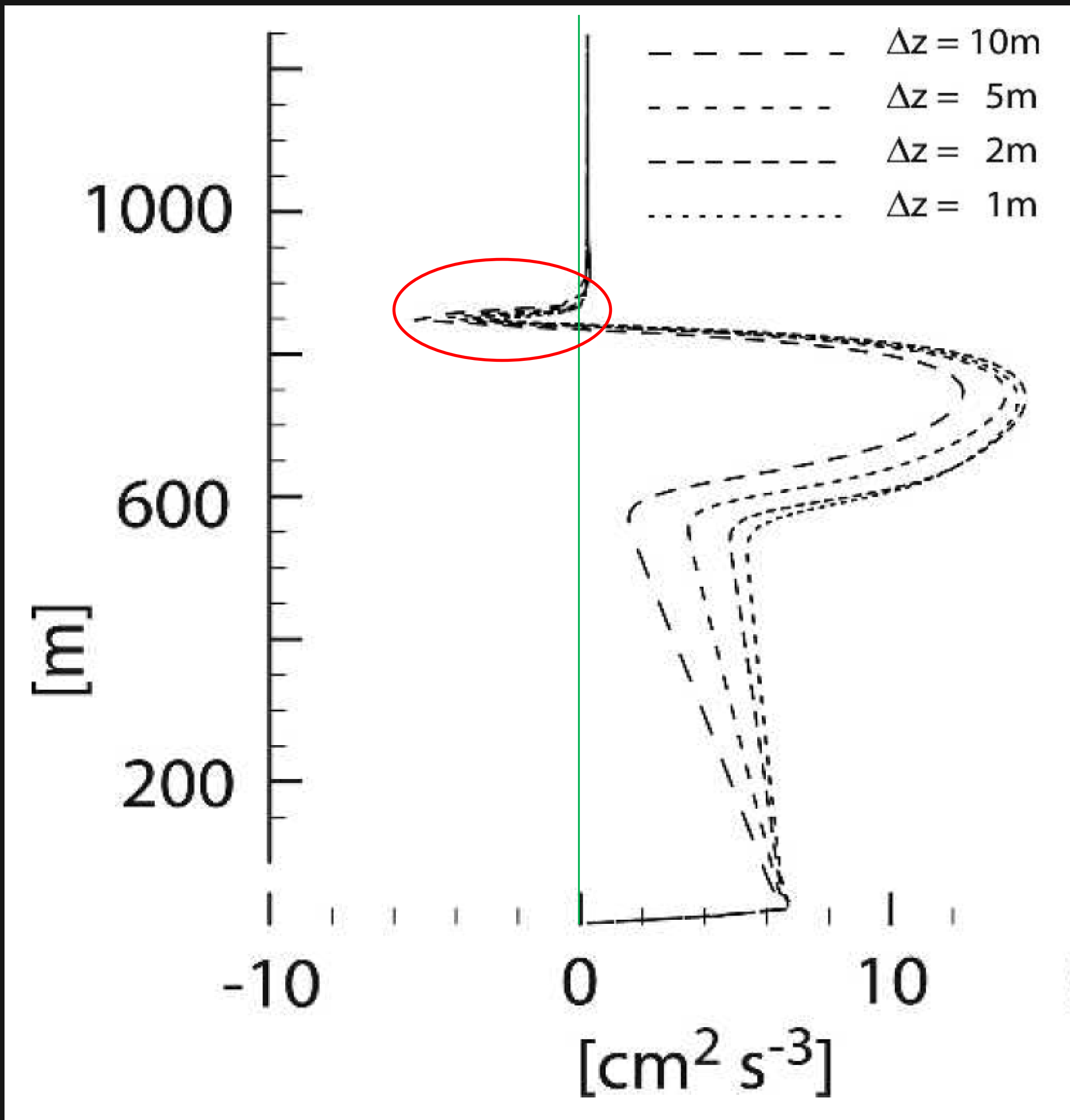
Turbulent kinetic energy (TKE) is <u>generated</u> when

- warm air moves upwards and
- cold air moves downwards

i.e. when buoyancy flux is positive.

Caused by cloud top IR radiative cooling

Buoyancy flux profile in stratocumulus



Stevens et al., Mon. Wea. Rev., 2005

TKE is consumed when

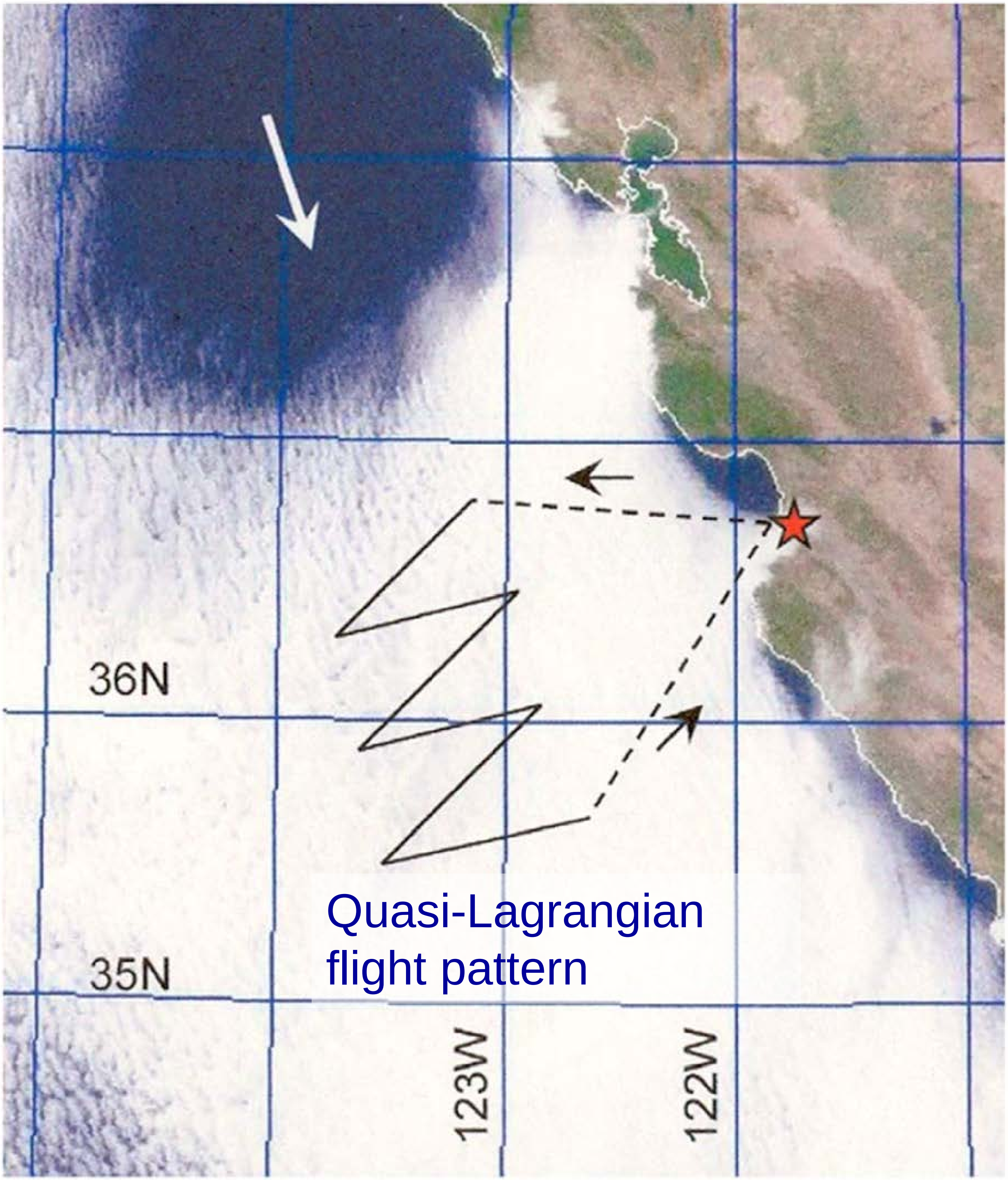
- warm air forced downwards (entrainment) and
- cold air forced upwards (detrainment)

i.e. when buoyancy flux is negative.

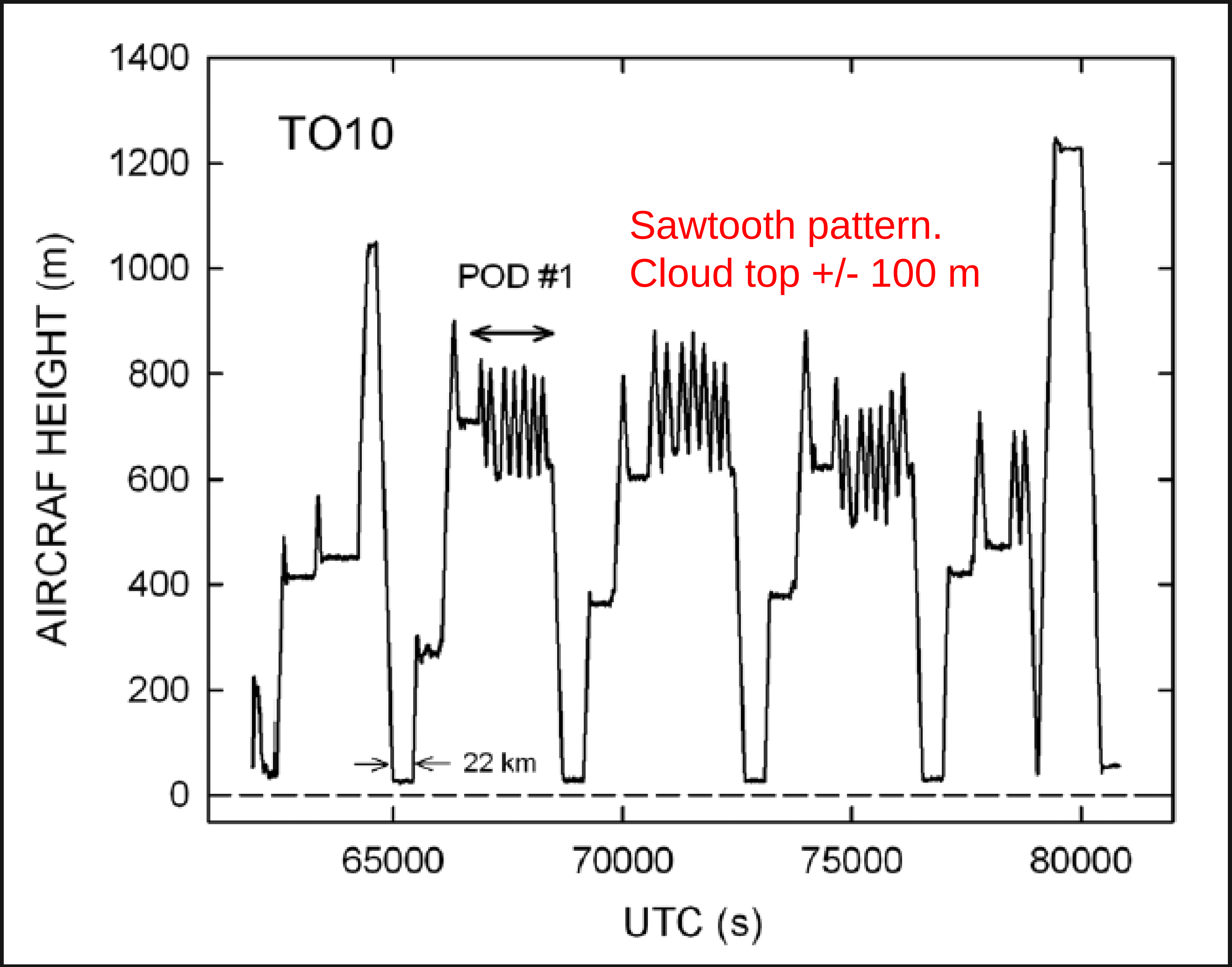
Observations from the Physics of Stratocumulus Top (POST) field campaign

CIRPAS Twin Otter.

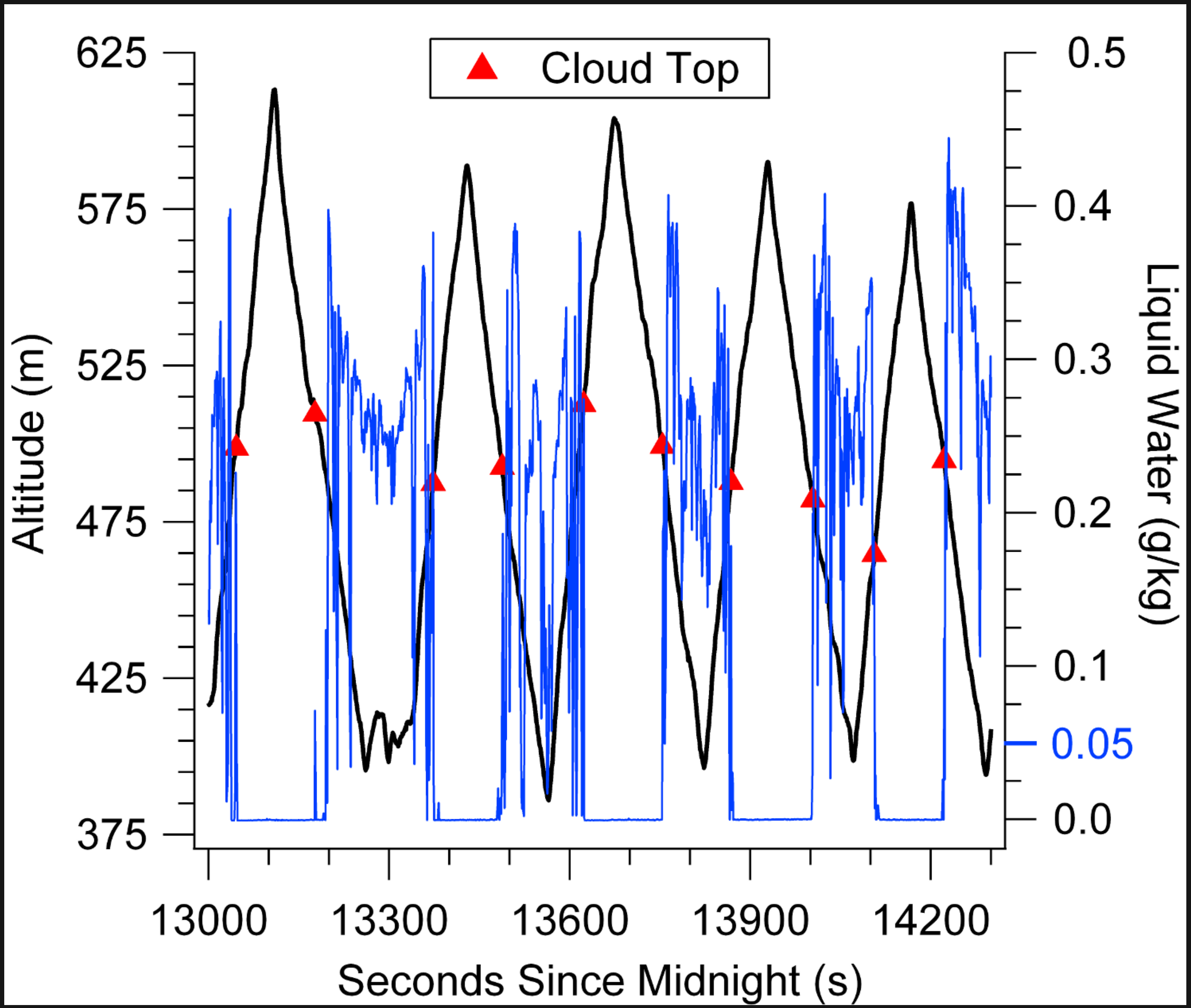
Map of study area

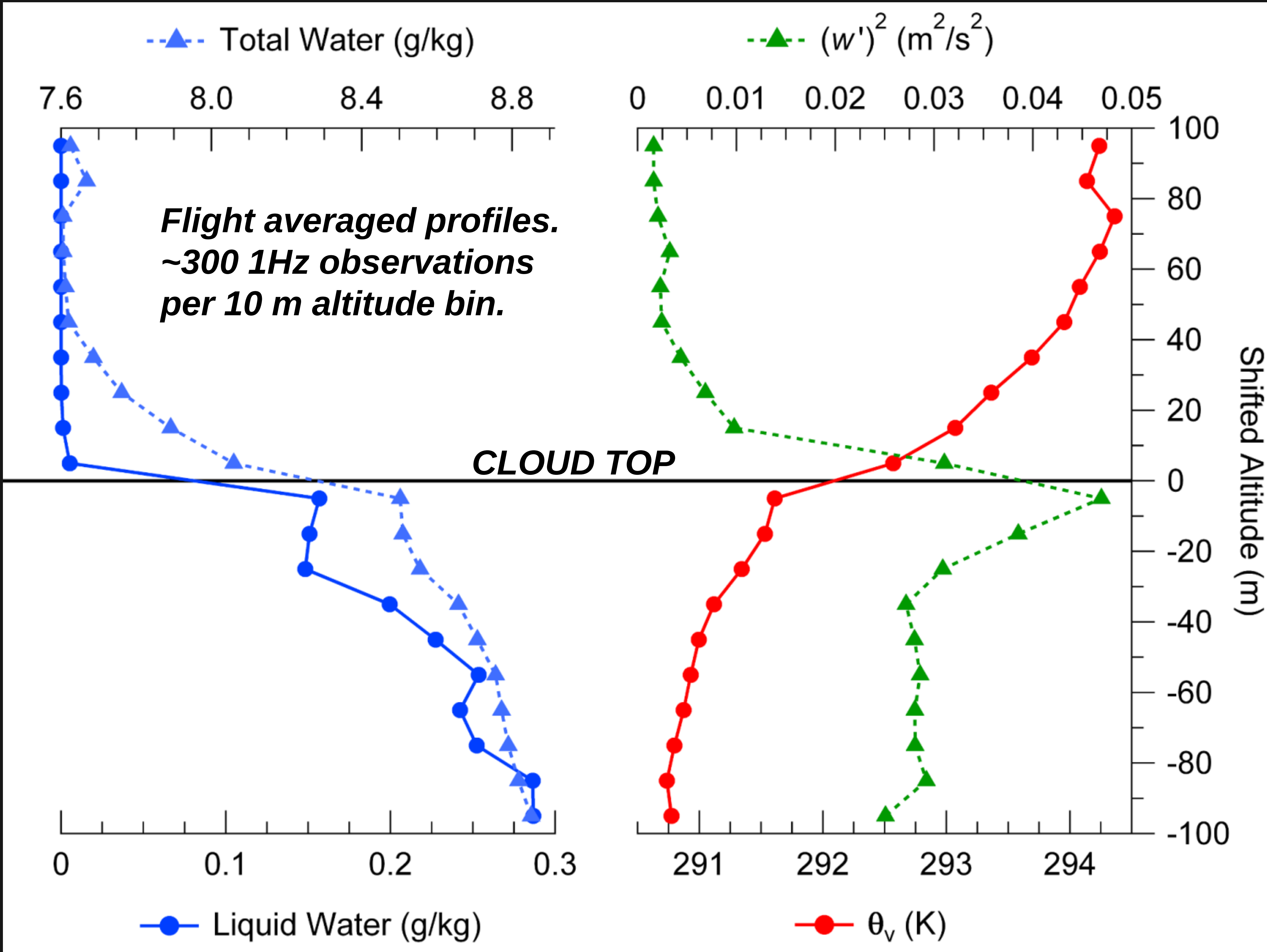


Typical flight pattern (vertical profile)



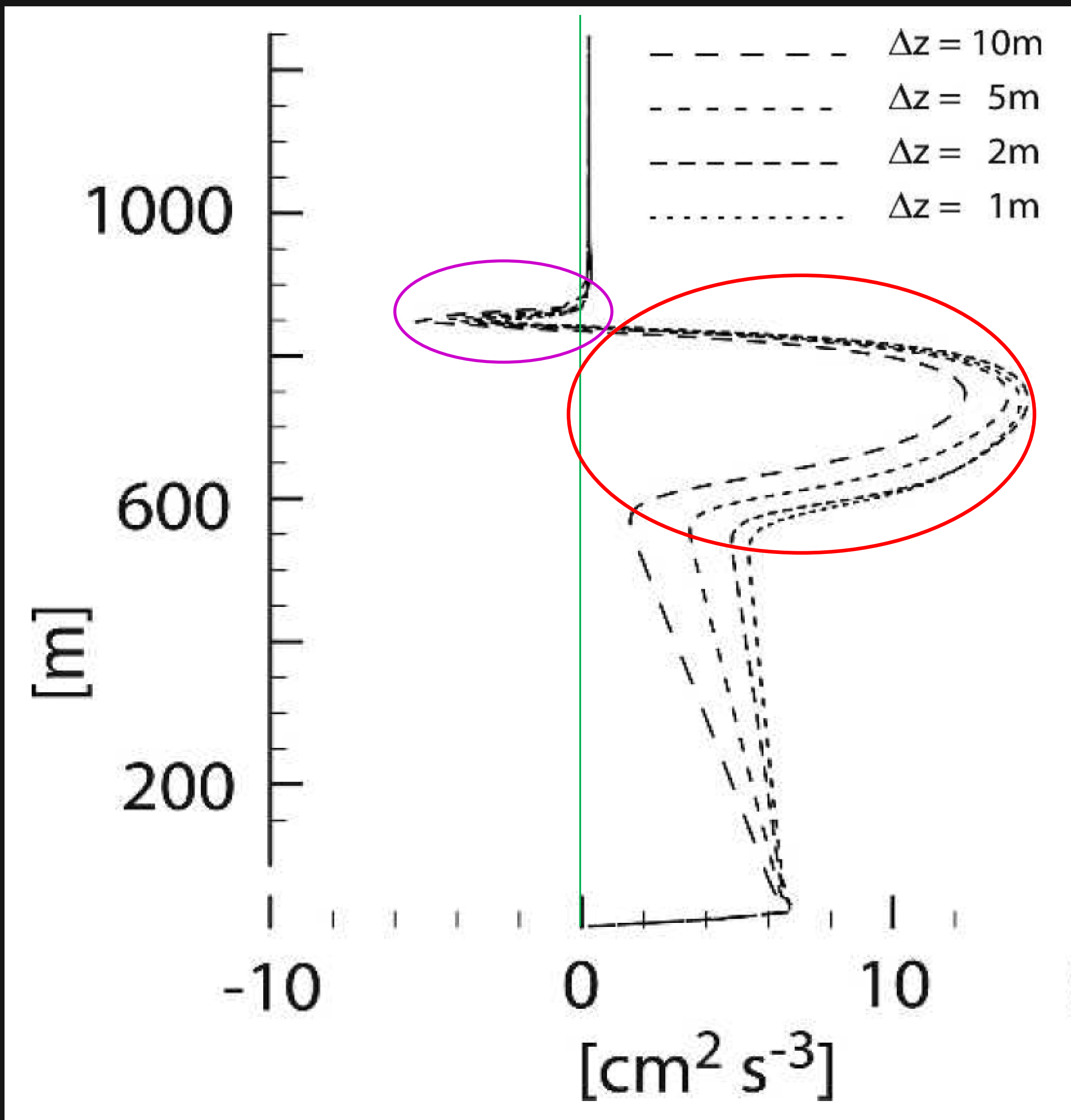
Data are analyzed to generate profiles referenced to cloud top at 10 m resolution





Total Water (g/kg)
$(w')^2$ (m^2/s^2)
7.6
8.0
8.4
8.8
0
0.01
0.02
0.03
0.04
0.05
Flight averaged profiles.
~300 1Hz observations
per 10 m altitude bin.
CLOUD TOP
100
80
60
40
20
0
-20
-40
-60
-80
-100
Shifted Altitude (m)
0
0.1
0.2
0.3
291
292
293
294
Liquid Water (g/kg)
θ_v (K)

How about buoyancy flux profiles?



Stevens et al., Mon. Wea. Rev., 2005

What we wish to compute (per Kraus and Schaller 1978):

$$r = -\frac{\int_{p_b}^{p_s} (F_{sv} < 0)\, dp}{\int_{p_b}^{p_s} (F_{sv} > 0)\, dp} =$$

Caveat #1: fluxes calculated from sawtooth sampling

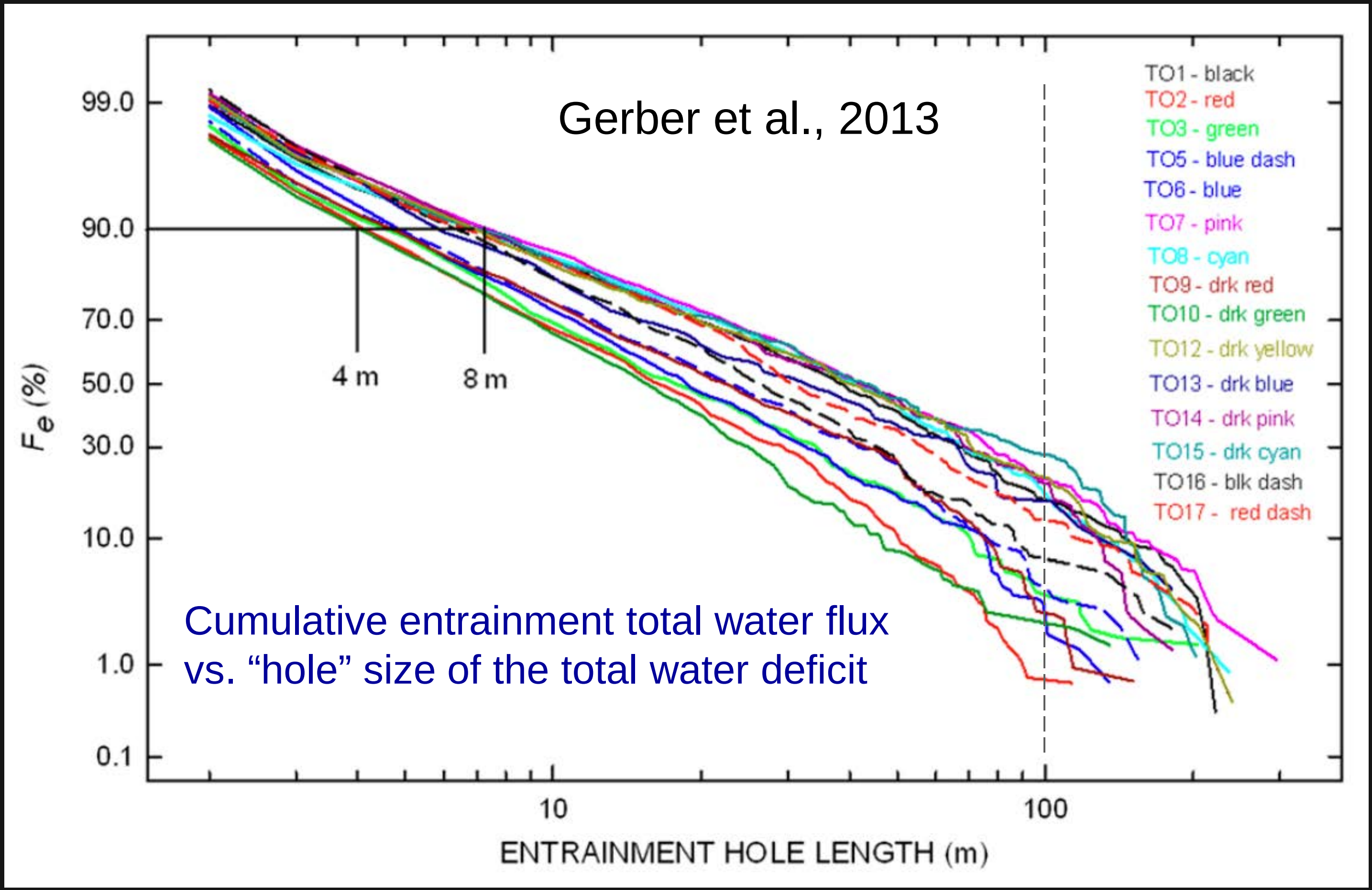
- Normally, turbulent fluxes are calculated from a level leg. That is not possible for these flight patterns.
- Instead, we utilize the following method:

1. Compute $\overline{w}$ and $\overline{\theta_\mathrm{v}}$ for each 2-s interval using the 40 Hz data set, which corresponds to a period where the altitude change is $\sim$3 m, while the horizontal distance travelled is 110 m. The latter value sets the characteristic length scale for the filtered fluxes.
2. Compute w' and θ'_v as usual from 40 Hz data, e.g. $w' = w - \overline{w}$.
3. Compute $\overline{w'\theta'_\mathrm{v}}$.
4. We now treat each 2-s value as a single average value, which we then bin into shifted altitude bins as described above.

Caveat #1: Fluxes calculated are spatially filtered

- The result of this method are small-scale, filtered fluxes. That is, the fluxes correspond to turbulent transport by eddies of size ~100 m and below.

- This might be OK for estimating negative buoyancy fluxes in the vicinity of cloud top associated with entrainment…



Caveat #1: Fluxes calculated are spatially filtered

- The result of this method are small-scale, filtered fluxes. That is, the fluxes correspond to turbulent transport by eddies of size ~100 m and below.

- … but must UNDERESTIMATE the positive buoyancy flux driving boundary layer turbulence.

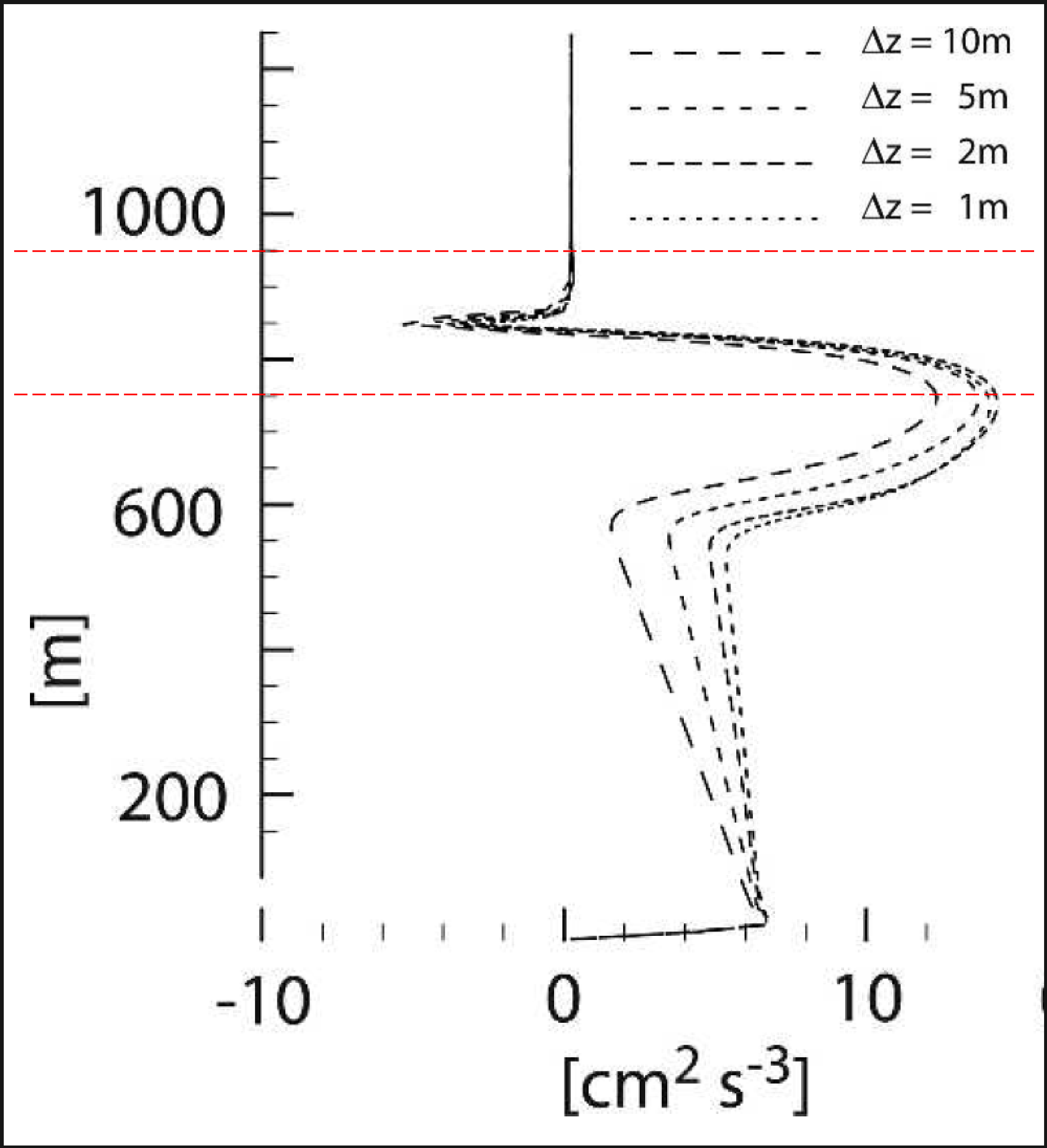
- The eddies that dominate the transport have a size ~boundary layer depth, which is ~200 to 400 m.

Caveat #2: Sawtooth sampling does not extend through the entire boundary layer

Data are collected only for cloud top +/- 100 m

… which also leads to an UNDERESTIMATE of the positive buoyancy flux associated with cloud top cooling.

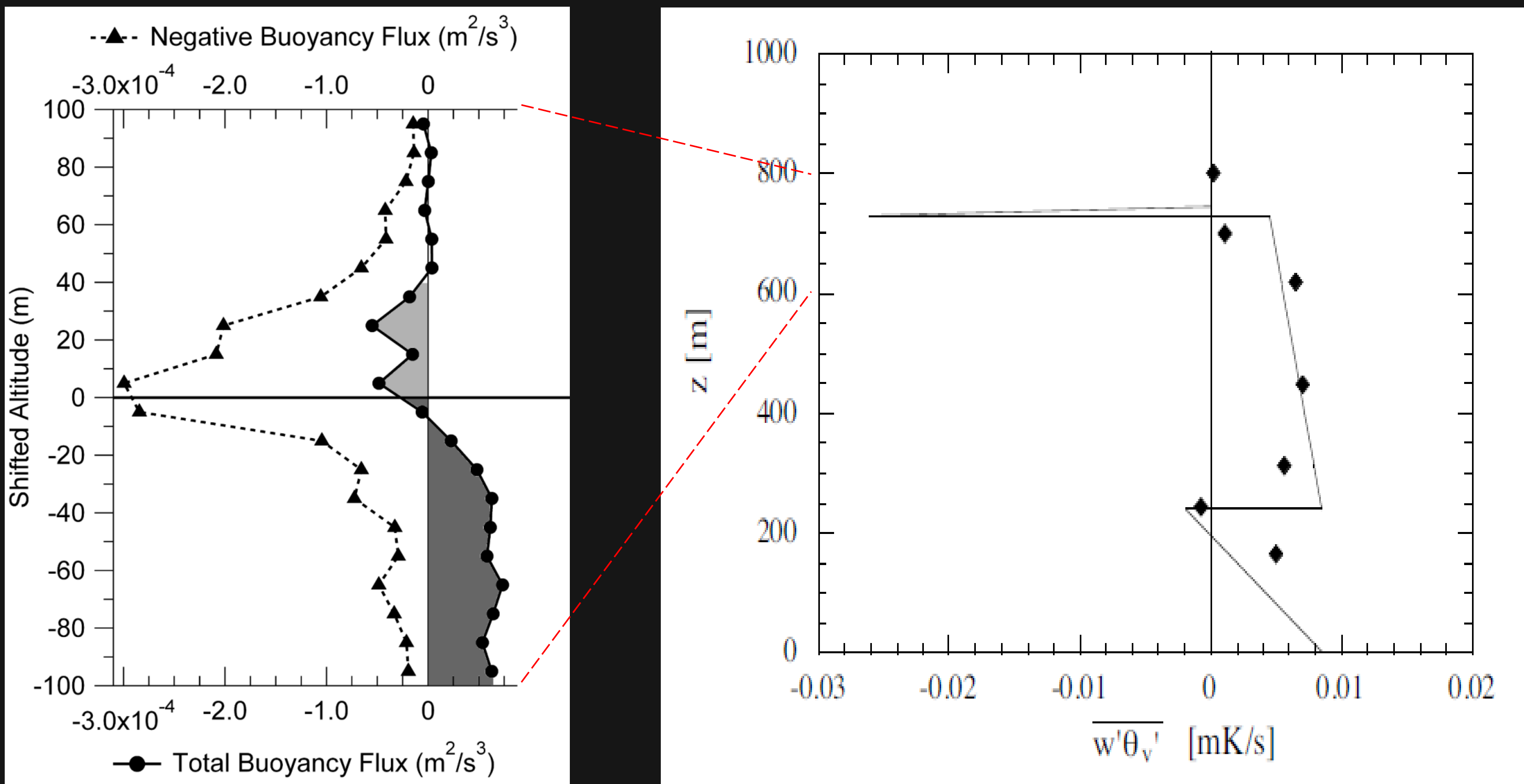
Sampling range



Stevens et al., Mon. Wea. Rev., 2005

Advantages of the sawtooth sampling!

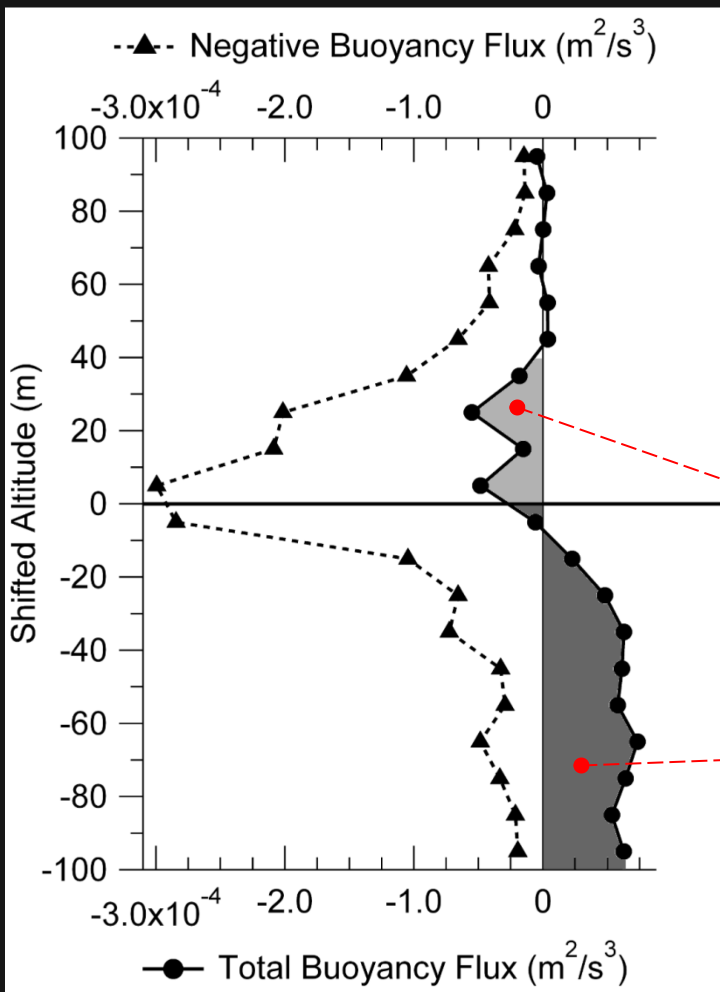
- Resolve the sharp features of the buoyancy flux profile



Duynkerke 1995

Advantages of the sawtooth sampling!

- Resolve the sharp features of the buoyancy flux profile



What we wish we could compute (per Kraus and Schaller 1978):

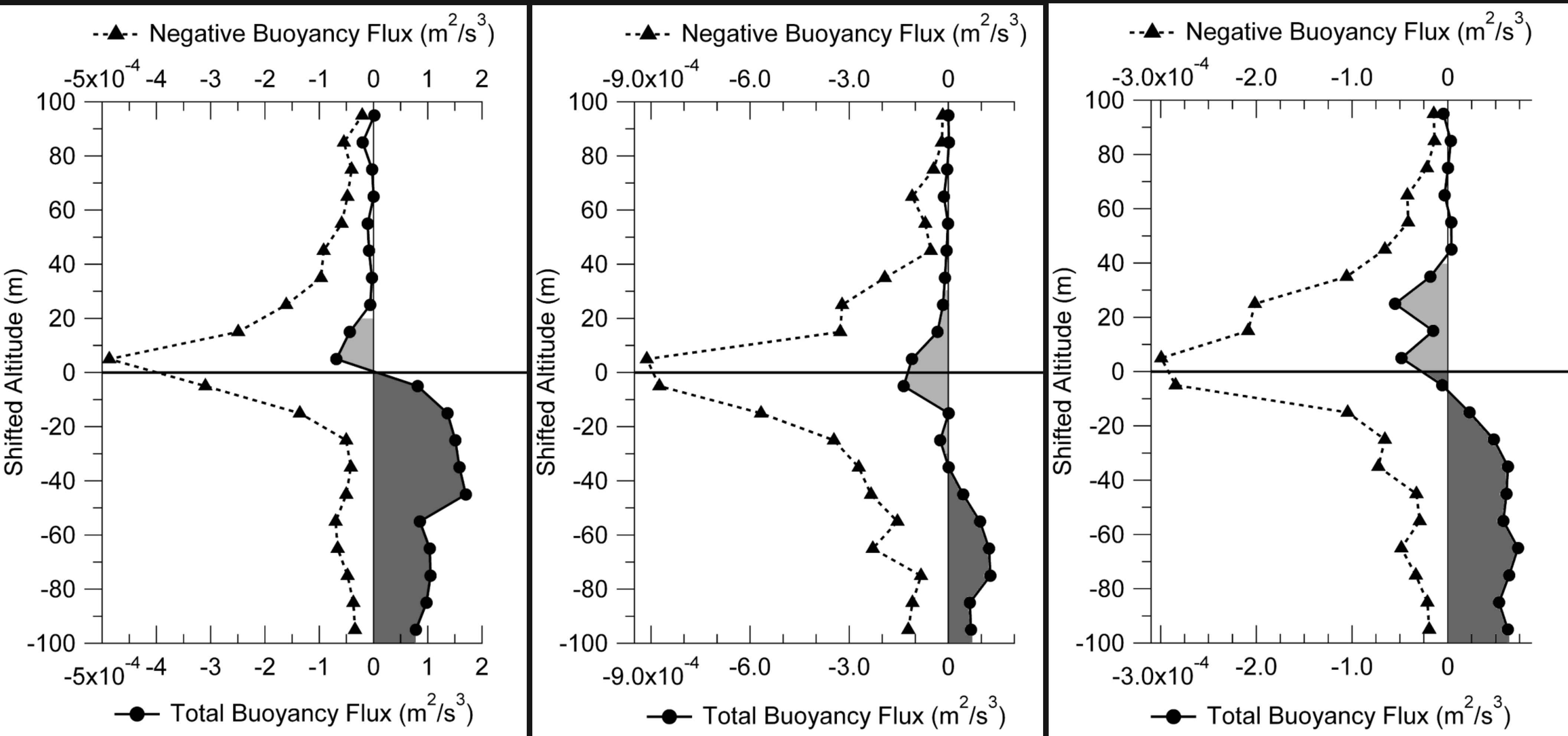
$$r = -\frac{\int_{p_b}^{p_s} (F_{sv} < 0)\, dp}{\int_{p_b}^{p_s} (F_{sv} > 0)\, dp} =$$

What we <u>are</u> able to compute:

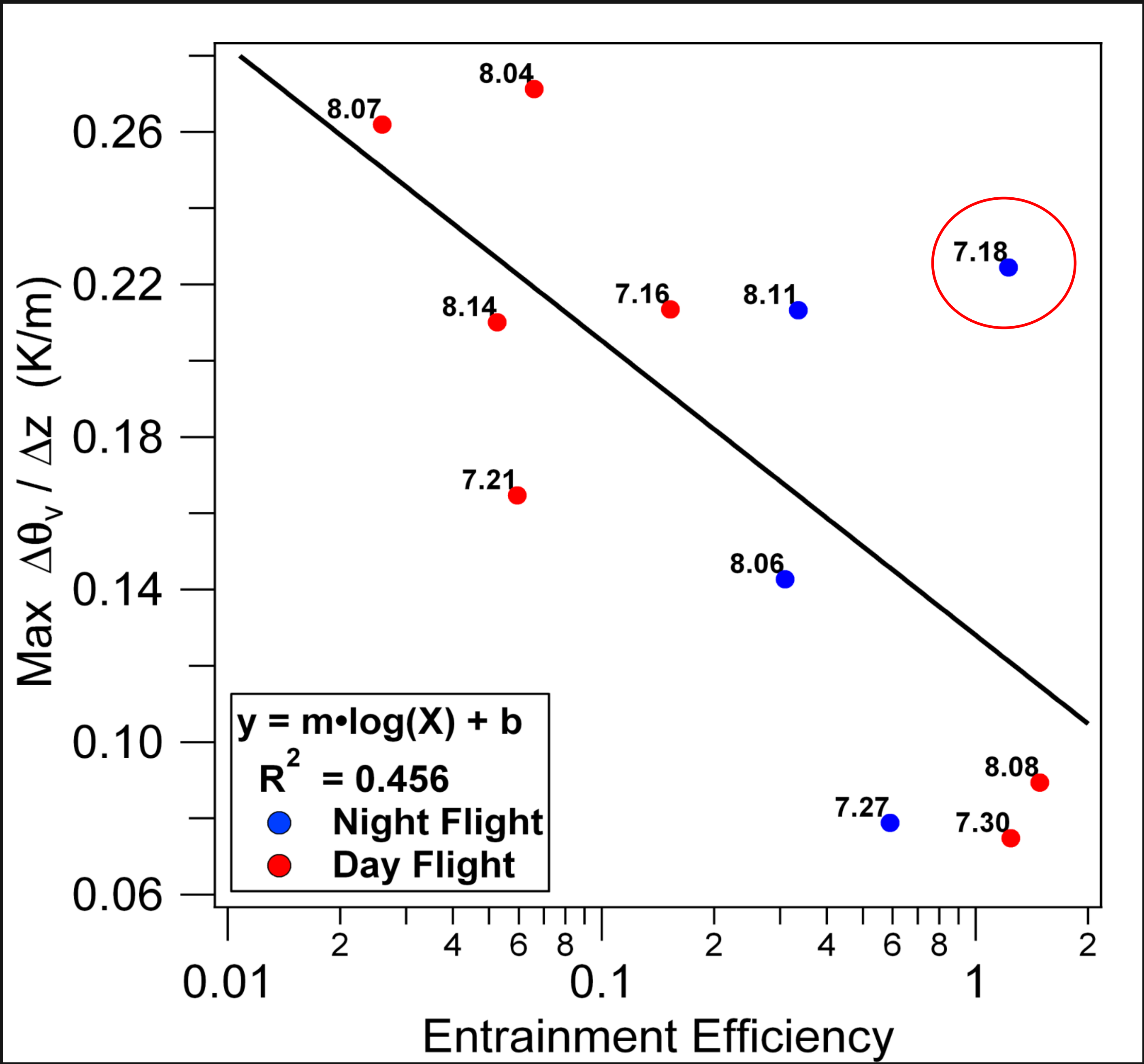
$$r = -\frac{\int_{z_{\mathrm{s,min}}}^{z_{\mathrm{s,max}}} (\overline{w'\theta'_{\mathrm{v}}}\,|_{\ell} < 0)\, dz_{\mathrm{s}}}{\int_{z_{s,min}}^{z_{\mathrm{s,max}}} (\overline{w'\theta'_{\mathrm{v}}}\,|_{\ell} > 0)\, dz_{\mathrm{s}}}$$

We'll term this ratio *r* the "entrainment efficiency"

Example buoyancy flux profiles from three different days



What does entrainment efficiency depend on?



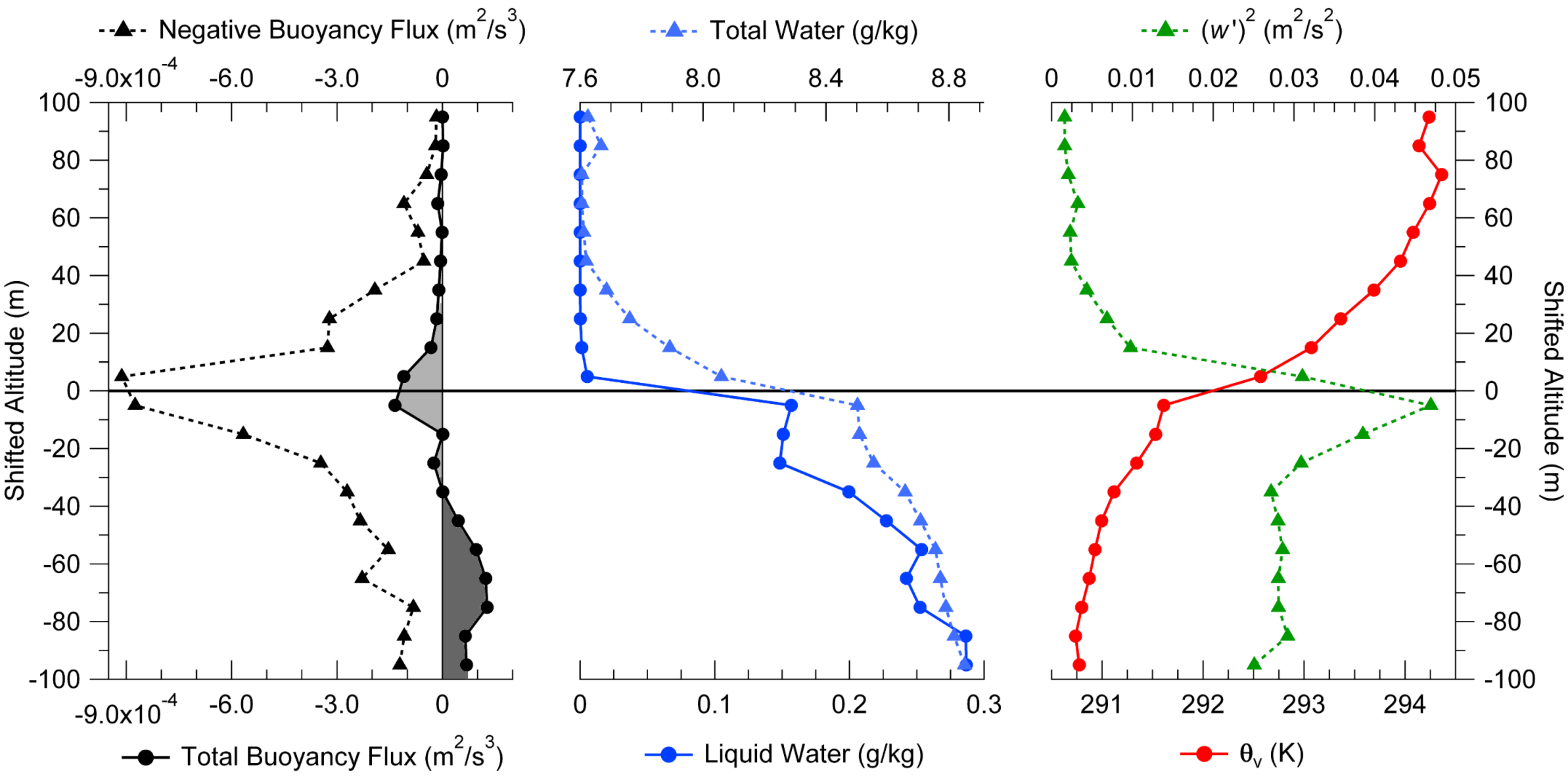
Cloud top stratification!

The stronger the cloud top θ_v inversion, the weaker the entrainment efficiency.

That is, stronger stratification reduces the fraction of the available energy that is converted into entrainment.

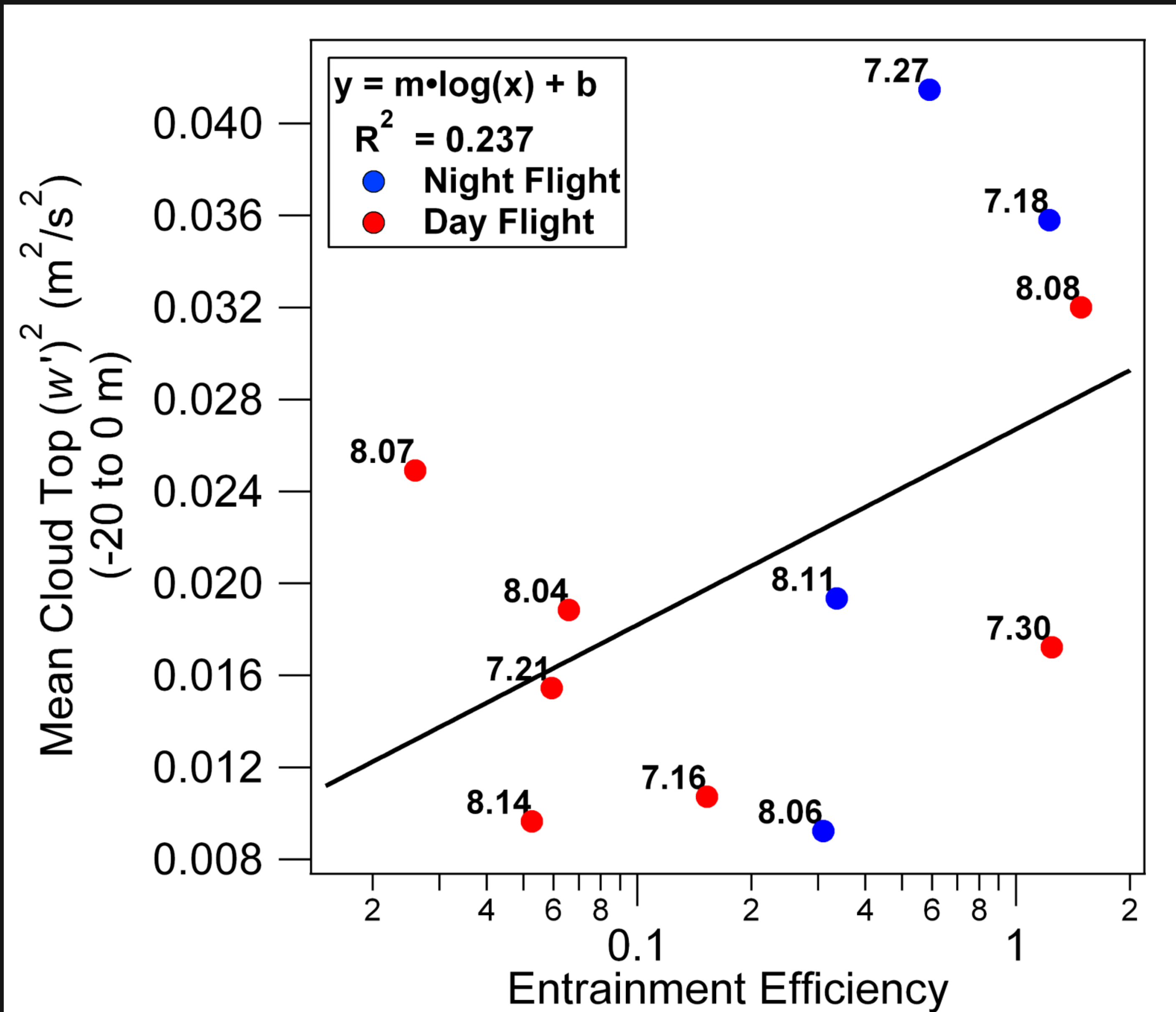
Range of entrainment efficiency values is a factor of ~30.

Not a constant as in Kraus & Schaller 1978.



Negative Buoyancy Flux (m^2/s^3)
Total Water (g/kg)
$(w')^2$ (m^2/s^2)
$-9.0x10^{-4}$
-6.0
-3.0
0
7.6
8.0
8.4
8.8
0
0.01
0.02
0.03
0.04
0.05
100
80
60
40
20
0
-20
-40
-60
-80
-100
Shifted Altitude (m)
0.1
0.2
0.3
291
292
293
294
Total Buoyancy Flux (m^2/s^3)
Liquid Water (g/kg)
θ_v (K)

What does entrainment efficiency not depend on?



No relationship with cloud top $(w')^2$ is found.

While TKE is a key control of the entrainment flux, we see no evidence that it affects the entrainment efficiency.

Conclusions

- The fraction of the boundary layer TKE that is consumed in entrainment varies by a factor of ~30.
  - Deardorff (1980) found a factor of ~10.

- This entrainment efficiency decreases as the cloud top stratification strengthens.

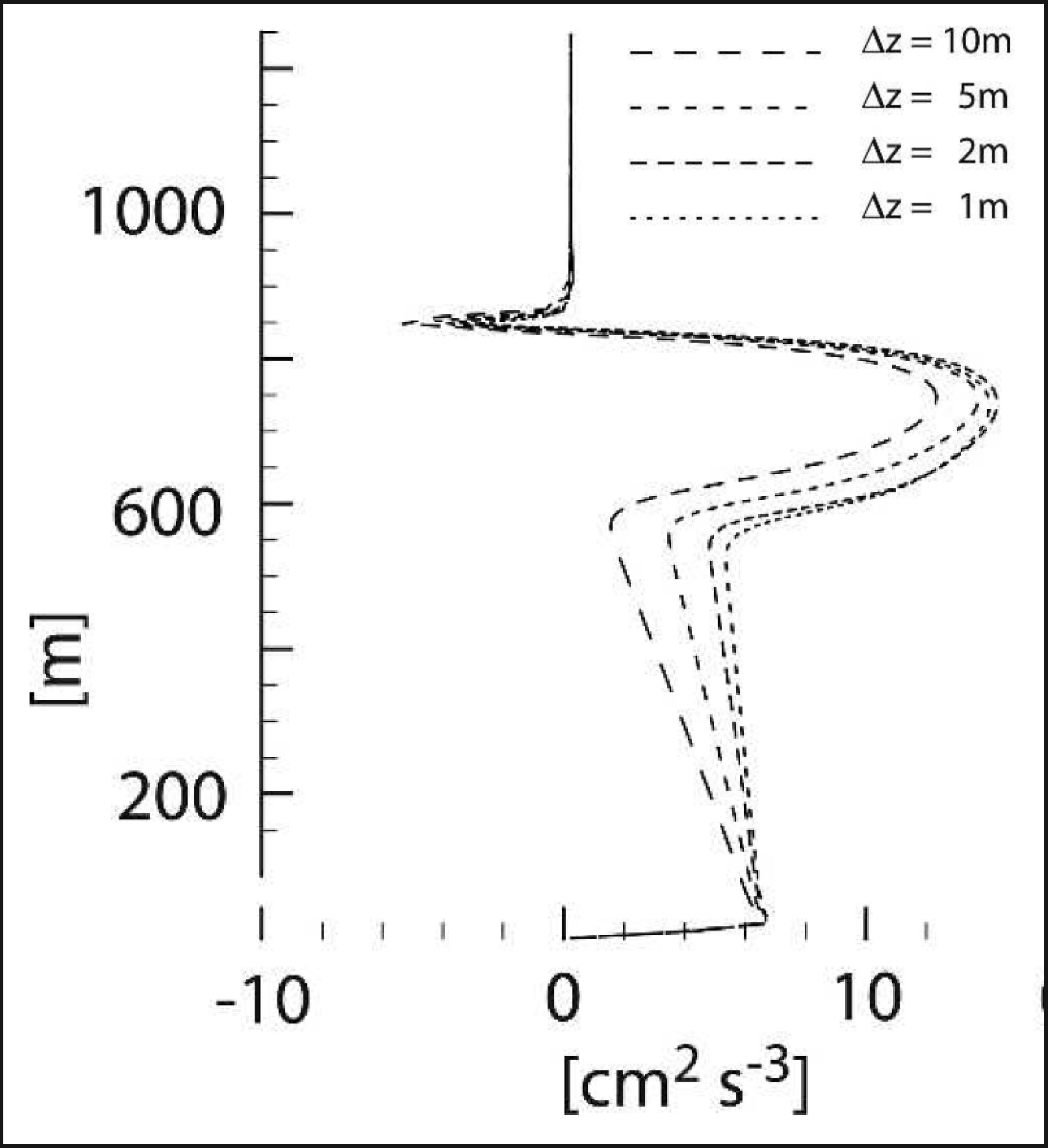
- Entrainment efficiency does not appear to depend on the magnitude of TKE at cloud top or in the boundary layer.

- Do models exhibit the same behavior?

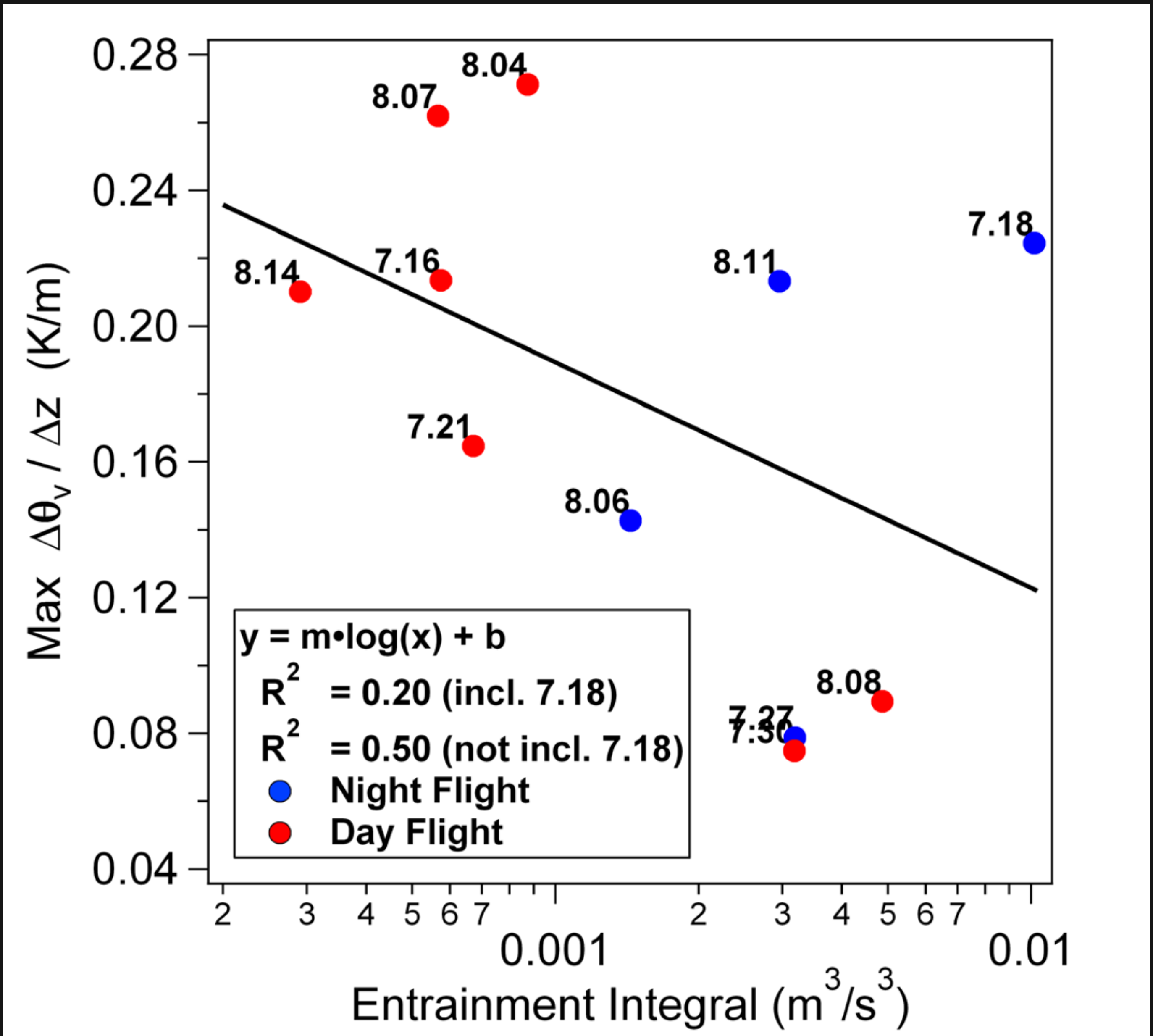
- Will future changes in stratification affect stratocoumulus entrainment?

Thanks!

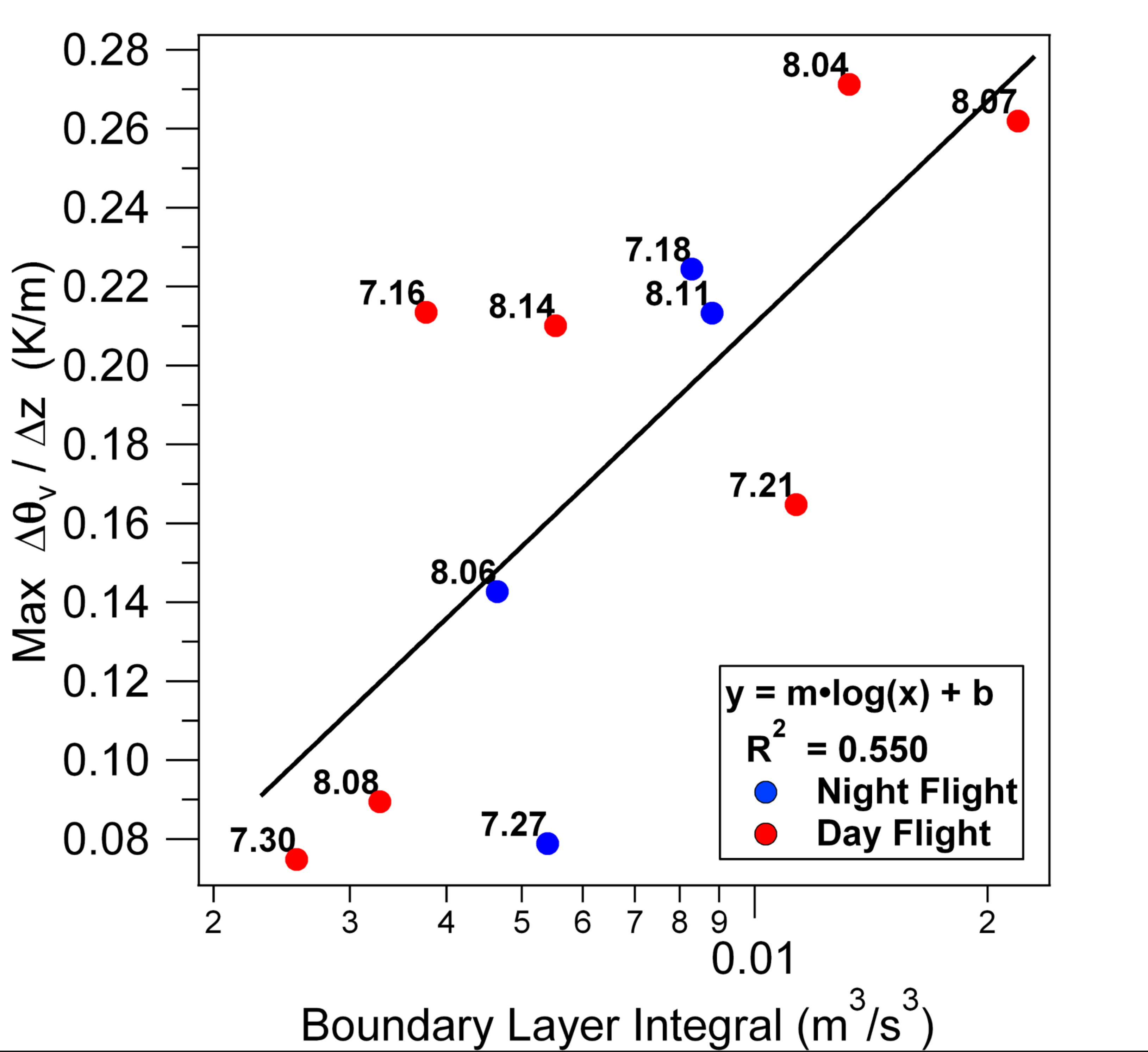
Resolving fluxes at 3 m vertical resolution appears sufficient, especially in the cloud top region.



Stevens et al., Mon. Wea. Rev., 2005



0.28
0.24
0.20
0.16
0.12
0.08
0.04
Max $\Delta\theta_v$ / Δz (K/m)
2 3 4 5 6 7
0.001
2 3 4 5 6 7
0.01
Entrainment Integral (m^3/s^3)
8.04
8.07
8.14
7.16
7.18
8.11
7.21
8.06
8.08
7.27
7.30
y = m•log(x) + b
R^2 = 0.20 (incl. 7.18)
R^2 = 0.50 (not incl. 7.18)
Night Flight
Day Flight



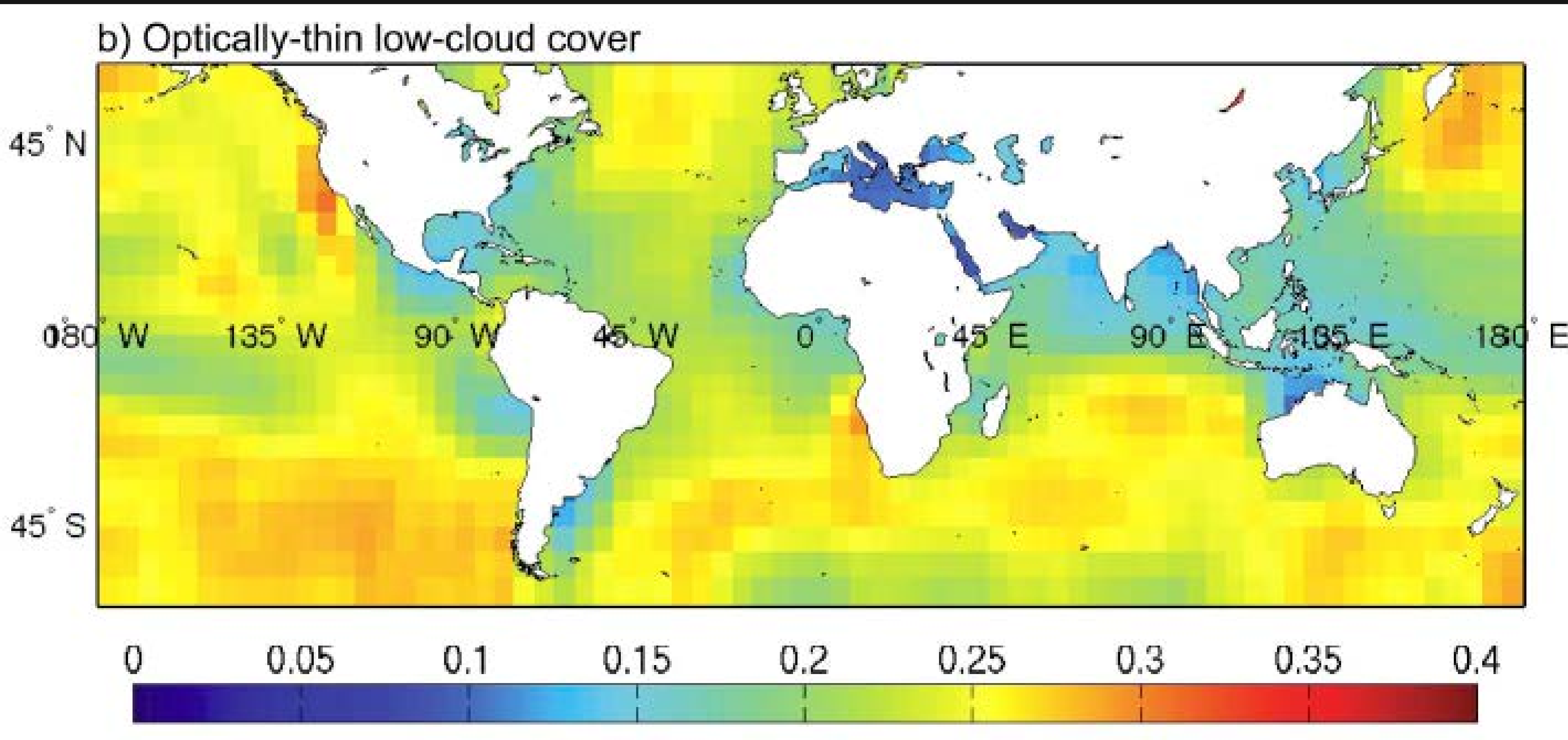
Max $\Delta\theta_v / \Delta z$ (K/m)
Boundary Layer Integral (m^3/s^3)
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
2
3
4
5
6
7
8
9
0.01
2
8.04
8.07
7.18
7.16
8.14
8.11
7.21
8.06
8.08
7.30
7.27
y = m•log(x) + b
R^2 = 0.550
Night Flight
Day Flight

Table 1. Average Properties Calculated From 10 Vertical Profiles for Each POST Flight[a]

Flight		Date (UTC)	z_i (m)	$z_i - z_o$ (m)	Δz (m)	dz_i/dt (cm/s)	T_i (°C)	ΔT (°C)	LWC_i (g/m^3)	q_{vi} (g/kg)	Δq_v (g/kg)	U_i (m/s)	U_s (1/s)	$U_{\theta i}$ (deg)	$U_{\theta s}$ (deg)
TO1[b]	D	7/16	560	365	34	−0.17	10.6	5.9	0.48	8.66	+2.02	8.40	0.056	336	+22
TO2[b]	D	7/17	529	219	32	−0.49	9.8	7.4	0.33	7.99	−2.72	11.0	0.119	336	−23
TO3[b]	N	7/19	500	264	52	+0.35	10.3	10.1	0.46	8.29	−3.65	14.5	0.183	333	+14
TO5[bc]	N	7/28	486	253	41	+0.76	10.8	2.8	0.30	8.70	−0.71	11.6	0.352	335	+2
TO6[b]	N	7/29	638	275	20	−1.32	9.4	7.5	0.50	7.88	−5.94	9.50	0.151	331	−1
TO7	D	7/30	375	282	50	+0.01	12.7	2.9	0.33	9.06	−0.27	13.2	0.108	330	+9
TO8[bc]	D	8/1	413	82	43	−0.68	12.8	3.5	0.22	9.73	−0.83	17.4	0.133	340	+8
TO9[d]	D	8/2	182	127	57	+0.08	11.4	8.3	0.21	8.61	−0.88	12.7	0.092	324	+5
TO10	D	8/4	635	269	34	−2.30	9.7	8.7	0.39	8.04	−5.70	9.9	0.183	331	+3
TO12	N	8/8	760	329	29	−0.62	9.0	8.9	0.50	7.81	−4.67	6.5	0.235	320	−24
TO13[c]	N	8/9	654	409	59	+0.93	10.4	2.3	0.29	8.50	−0.49	10.9	0.190	328	+2
TO14	N	8/12	545	416	31	−0.08	11.7	6.4	0.59	9.22	−1.47	13.9	0.069	333	+6
TO15	N	8/13	495	314	62	+0.79	10.5	9.5	0.03	9.00	−1.30	14.6	0.141	341	+13
TO16[e]	D	8/14	457	326	70	+0.38	11.5	10.2	0.42	9.00	−3.04	7.6	0.099	325	+5
TO17	D	8/15	454	329	59	+0.08	11.8	6.8	0.47	9.12	+0.21	9.3	0.093	330	−7
POST Mean			513	284	45		10.8	6.7	0.39	8.64	−1.96	11.4	0.145	332	+2
DYCOMS II Mean			756	360	23		11.6	8.2	0.67	9.36	−5.93				

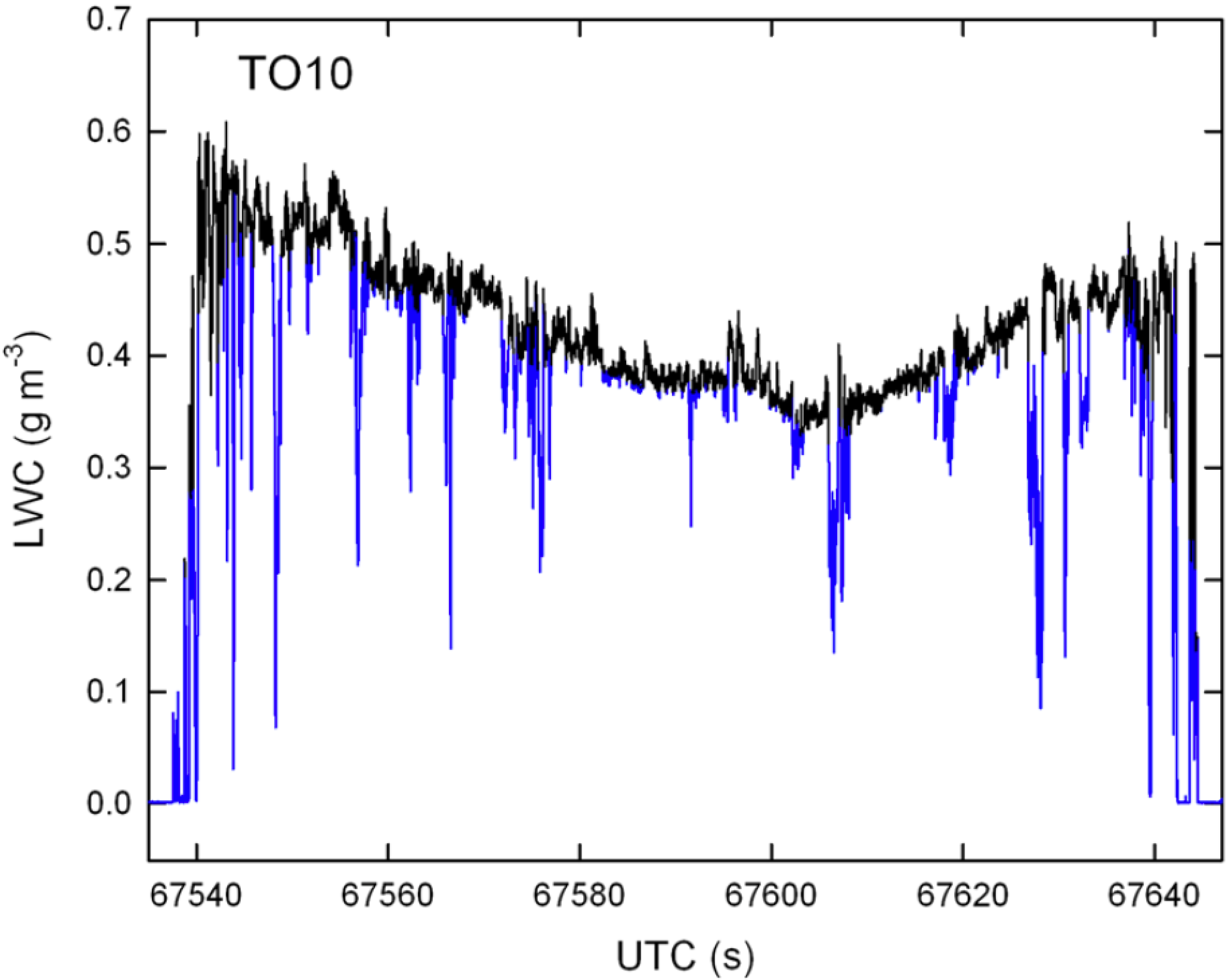
[a]z_i, height of cloud top; z_o, height of cloud base; Δz, height change across the entrainment interface layer (EIL); dz_i/dt, rate of change of cloud top; T_i, temperature at cloud top; ΔT, temperature jump across EIL; LWC_i, liquid water content at cloud top; q_{vi}, vapor mixing ratio at cloud top; Δq_v, jump of vapor mixing ratio across EIL; U_i, wind speed at cloud top; U_s, wind shear above cloud top; $U_{\theta i}$, wind direction at cloud top; $U_{\theta s}$, change in wind direction between z_i and the top of the EIL; D, day flight; N, night flight.

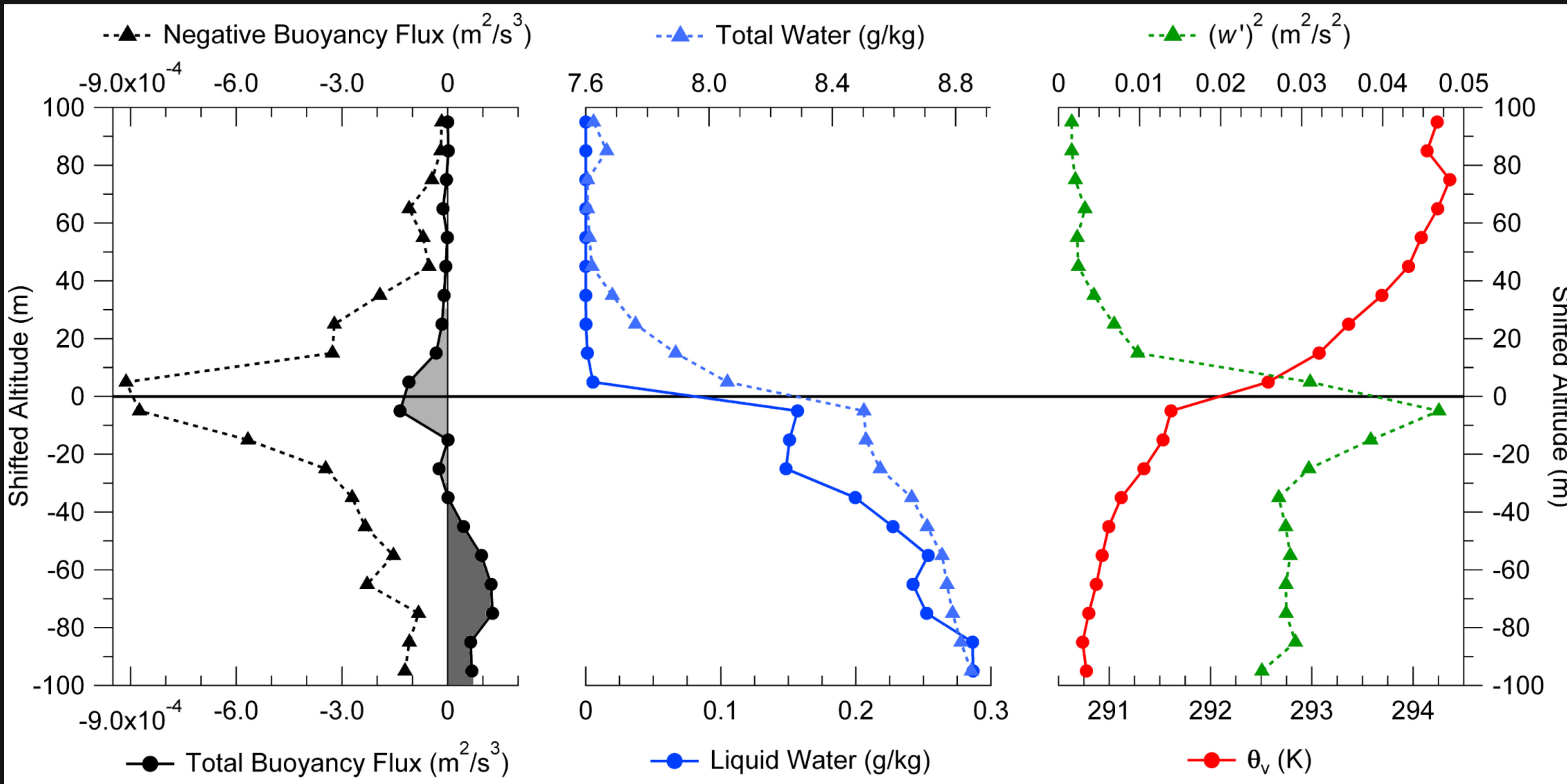
Optically thin (and hence non-drizzling) clouds may be more prevalent that previously thought.



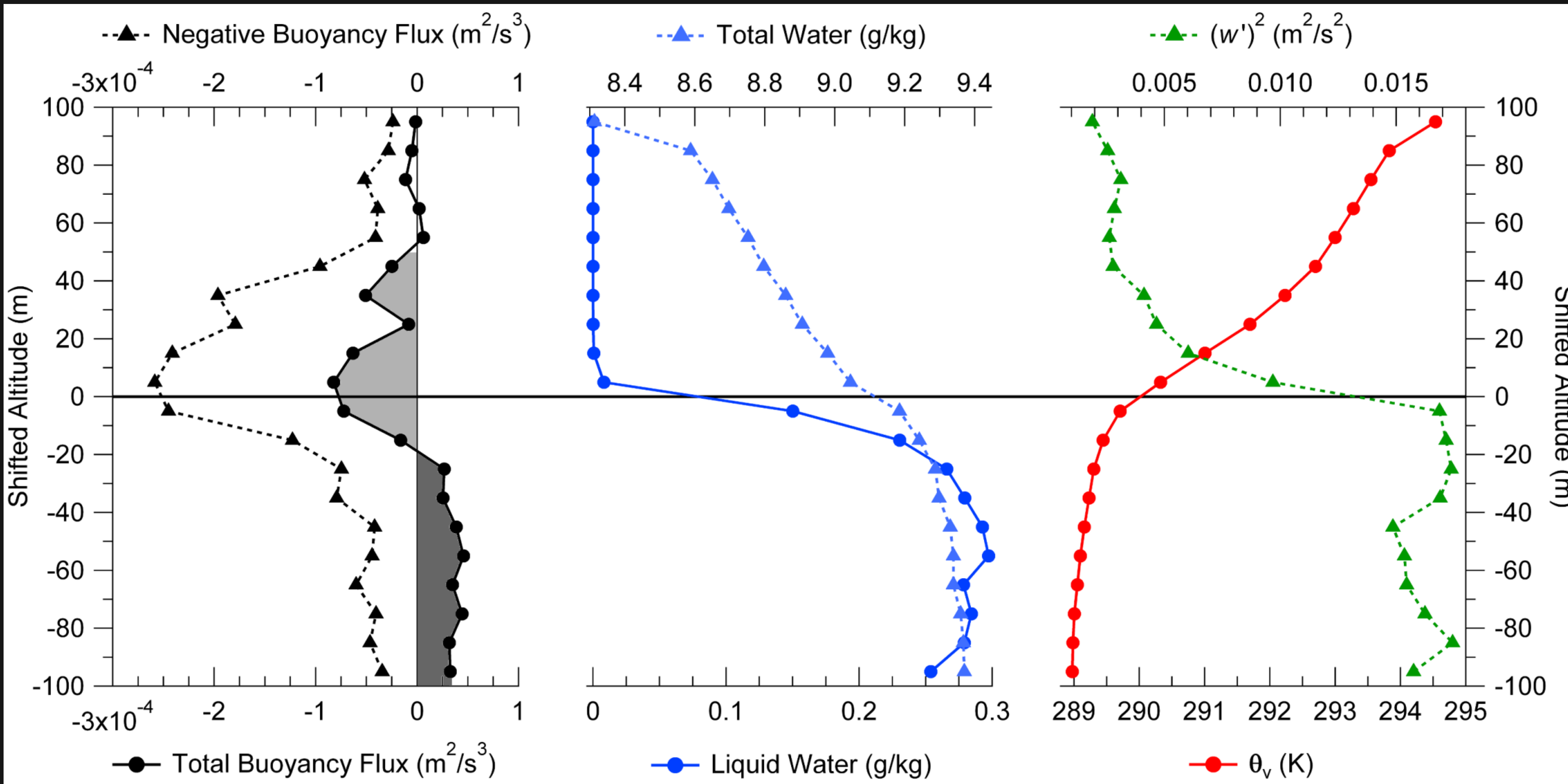
Leahy et al., JGR, 2012

CALIPSO satellite measurements

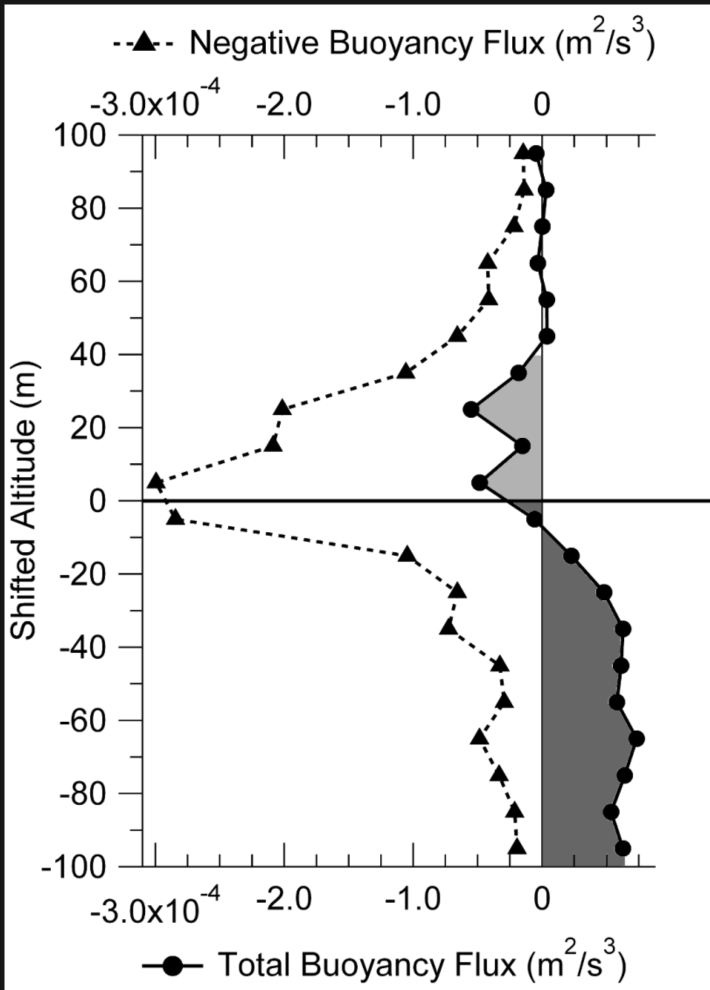

TO10
LWC (g m-3)
UTC (s)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
67540
67560
67580
67600
67620
67640



Negative Buoyancy Flux (m^2/s^3)
Total Water (g/kg)
(w')^2 (m^2/s^2)
Shifted Altitude (m)
Total Buoyancy Flux (m^2/s^3)
Liquid Water (g/kg)
θv (K)



Negative Buoyancy Flux (m2/s3)
Total Water (g/kg)
(w')2 (m2/s2)
-3x10-4
-2
-1
0
1
8.4
8.6
8.8
9.0
9.2
9.4
0.005
0.010
0.015
Shifted Altitude (m)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0.1
0.2
0.3
289
290
291
292
293
294
295
Total Buoyancy Flux (m2/s3)
Liquid Water (g/kg)
θv (K)


Negative Buoyancy Flux (m²/s³)
-3.0x10⁻⁴
-2.0
-1.0
0
Shifted Altitude (m)
100
80
60
40
20
0
-20
-40
-60
-80
-100
Total Buoyancy Flux (m²/s³)

Entrainment in cloud-topped boundary layers

- Typically, stratocumulus entrainment is parameterized as

$$\frac{w_e}{U} = \frac{a}{Ri_U}$$

where *U* is the convective velocity scale and *a* is an experimentally-determined parameter.

JAS, 1977

* *a* can be a constant, or it can be formulated to account for effects such as buoyancy reversal (e.g. Deardorff 1980; Randall 1980)

- Nichols and Turton (1986) evaluate a number of parameterizations against observations. They find that Kraus and Schaller (1978) is most successful. Kraus and Schaller propose a parameterization based on a buoyancy flux ratio:

$$r = -\frac{\int_{p_b}^{p_s} (F_{sv} < 0)\,dp}{\int_{p_b}^{p_s} (F_{sv} > 0)\,dp} = \text{constant}$$