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First International Satellite Land Surface Climatology Field Experiment 1987 sonde budget revisited

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Abstract. We recompute estimates of boundary layer top entrainment from the 1987 FIFE sonde data, using a better averaging method, and get a mean value for the entrainment parameter A_R of 0.39 ±0.19, about 10% smaller than before. We also show the dependence of A_R on wind speed and time of day. The increase in entrainment with wind speed is quite marked. Our mean asymptotic value of A_R, representative of free convection at low wind speeds, is now only 0.31.

1. Introduction

During the 1987 First International Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE), time series of visually tracked radiosondes carrying wet and dry bulb thermistors [see *Sugita and Brutsaert*, 1990a, b] were used to study the atmospheric boundary layer (BL) *Betts and Ball* [1994] used these and the FIFE surface flux data to calculate mean BL budgets and estimate entrainment rates. The technique they used was to select undisturbed days with sequences of usually eight sondes from near sunrise to sunset, scale them by BL depth, and then average the soundings at approximately the same time to describe the mean BL evolution for each of three intensive field campaigns (IFCs). There were 7, 13, and 6 days in each of their averages for IFC 2, IFC 3, and IFC 4 respectively. The surface flux data (already averaged over 17 stations in the FIFE 15 by 15 km site) were then averaged over these sets of days. A set of budget equations were presented by *Betts and Ball* [1994] (hereinafter referred to as BB94) to estimate fluxes at the inversion level from the budget of the nearly "mixed" layer (below the inversion base used for scaling) and the budget of the capping inversion itself. An entrainment "closure" parameter, A_R , relating surface (suffix s) and inversion layer base (suffix i) virtual heat fluxes (suffix θ_v) was then estimated from

$$F_{i\theta_v} = -A_R F_{s\theta_v} \quad (1)$$

They estimated A_R=0 44 ±0.21. Although the method is noisy and the authors neglected mean horizontal advection in the BL budget method, and mean vertical advection in the inversion level method, their analysis agreed with other FIFE studies, which suggested entrainment was significantly higher than the value of 0.2, considered representative of free convective BLs [Stull, 1988]. There was some indication in the data that A_R was higher on days of high wind.

The reason for this reanalysis is that following an extensive study of BL growth over the boreal forest *Barr et al.* (submitted manuscript, 1996), we believe that the analysis method of BB94 may be slightly biased on the high side. The reanalysis here follows the same equation set, but averages the same data differently. Our new mean value of A_R is 0.39 ±0.19, about 10% lower than in BB94, but still higher than the free convective value and the values found by *Barr et al.* (submitted manuscript, 1996) over the forest. However, when we account in more detail for the increase of A_R with windspeed, our asymptotic value for free convective conditions is reduced further to 0.31 (see later).

Barr et al. (submitted manuscript, 1996) explore several different ways of deriving an average BL budget from sonde sequences. The analysis of radiosondes suffers from a severe sampling problem. Individual sondes launched every 60 or 90 min are not representative of BL averages for, say, an hour. The BL is heterogeneous in its potential temperature (θ), mixing ratio (q), wind (V) and BL top pressure depth p_i on many spatial scales, but particularly on a convective scale of the order of a few kilometers. The advection distance in 1 hour is much larger (18 km at 5 m s^{-1}) than this convective scale,while each sonde takes only a few minutes to rise through the BL. This sampling problem is unavoidable until continuous sampling of θ, q, V and p_i from the surface becomes a routine technique. Forced to use sequences of radiosondes for BL budgets, one must average over many time intervals. BB94 first scaled sondes and then averaged the sondes in time blocks, corresponding to the launch times, which varied little from day to day (e.g., 1200 ±30 min). The rational for this approach is that it preserves the BL structure (which without scaling would be totally smoothed across the inversion because of the variation in BL depth). Their budget analysis used the averaged sonde time sequence for each IFC. This produces a relatively smooth time evolution of θ, q, and

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$\Delta P_i = p_i - p_s$, provided enough days are included. It also preserves the sample means of θ, q and ΔP_i. However, the inversion level θ flux is retrieved from the simplified mixed layer budget equation equation.. 5′ of BB94,

$$F_{i\theta} = F_{s\theta} + \frac{\Delta P_i}{g}\frac{\partial \langle\theta\rangle^{si}}{\partial t} \qquad (2)$$

where $\langle\,\rangle^{si}$ is a BL average and ΔP_i is negative. In finite difference form this equation is, for each sonde pair,

$$F_{i\theta} = F_{s\theta} + \frac{\widetilde{\Delta P_i}}{g}\frac{\delta\langle\theta\rangle^{si}}{\delta t} \qquad (3)$$

where the tilde is an average for the time step δt between sondes. The method of compositing soundings separately averages ΔP_i, $\delta\theta$, and δt over different days at similar times, before calculating $F_{i\theta}$. This method introduces some positive bias when compared to the better method of calculating $\Delta P_i\, \delta\theta/\delta t$ for each time step and then averaging; because ΔP_i and $\delta\theta/\delta t$ are inversely correlated. For a given surface heat flux, $\partial\theta/\partial t$ is larger if ΔP_i is small (BL is shallow). This means that for a similar time step (dropping the tilde),

$$|\overline{\Delta P_i \frac{\delta\langle\theta\rangle^{si}}{\delta t}}| < |\overline{(\Delta P_i)}\,\overline{\frac{\delta\langle\theta\rangle^{si}}{\delta t}}| \qquad (4)$$

where the overbar denotes an average over a set of days. Consequently, averaging over many days before calculating $F_{i\theta}$ in (2) overestimates $|F_{i\theta}|$. The bias is small, but we have seen it in both FIFE and Boreal Ecosystem-Atmosphere Study (BOREAS). Figure 1 illustrates this finding for the FIFE data. It shows $\delta\langle\theta\rangle^{si}/\delta t$ against BL depth ΔP_i for this FIFE data set, breaking the data into the time intervals during the day. The dashed line corresponds to a flux difference between top and bottom of the BL of 240 W m^{-2}. Although the scatter is large, the general inverse correlation of BL depth and $\delta\langle\theta\rangle^{si}/\delta t$ within each time block is apparent.

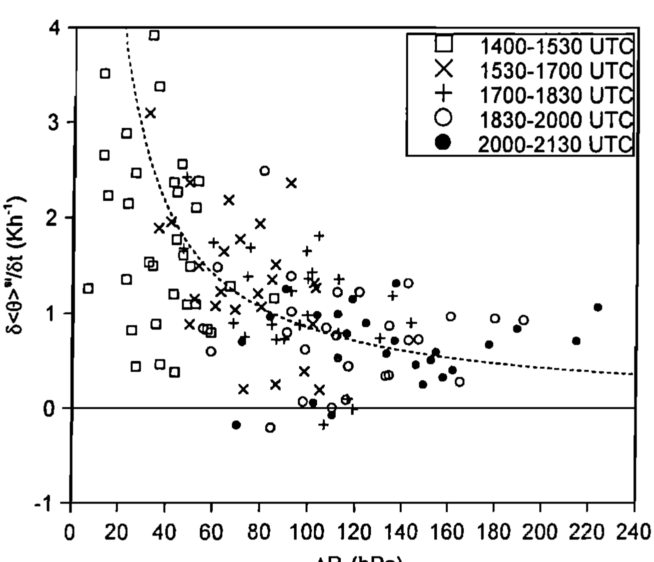

Figure 1. Plot of rate of boundary layer warming against boundary layer pressure depth.

In the inversion layer (IL) budget there is a similar bias issue in the estimate of

$$gF_{i\theta} = \delta p_i/\delta t(\theta_t - \langle\theta\rangle^{si}) - \Delta P\,\delta\langle\theta\rangle^{il}/\delta t \qquad (5)$$

where the inversion layer thickness $\Delta P = (p_t - p_i)$ is negative (there was a sign error in BB94 equation 10) and the superscript t denotes the top of the inversion layer. The first term is the dominant term, and the growth $\partial p_i/\partial t$ is larger if the inversion strength $(\theta_t - \langle\theta\rangle^{si})$ is small, so that again,

$$|\overline{\delta p_i/\delta t(\theta_t - \langle\theta\rangle^{si})}| < |\overline{\delta p_i/\delta t}\,\overline{(\theta_t - \langle\theta\rangle^{si})}| \qquad (6)$$

Again we found that first averaging the soundings from a set of days typically gives a slightly larger estimate of $|F_{i\theta}|$ in (5).

2. Results

Table 1 presents revisions to Tables 2 and 3 of BB94 based on calculating the entrainment fluxes from (3) and (5) for each sonde pair from 1400 to 2130 UTC and then averaging. As discussed above, we now believe that this method gives the most representative average of the noisy data. The changes from the tables of BB94 are relatively small, although estimates of A_R are reduced about 10%. The significant difference between the BL and IL budgets (which we noticed before) remains however, and for this we have no new insight. The IL budget neglects subsidence and may therefore underestimate entrainment. The BL budget ignored horizontal advection (which may be responsible for the large IFC 2 value). A simple average of the six estimates of A_R is 0.39 ±0.19.

The new averaging method enabled us to explore a little more throughly than BB94 the dependence of A_R on wind speed by grouping the sonde pairs into three wind speed classes before averaging. Table 2 shows that both methods of calculating A_R show an increase of entrainment with wind speed, although the BL budget method again gives systematically higher values than the IL budget. Table 2 certainly supports the hypothesis that shear-generated turbulence contributes significantly to entrainment, although the low wind value is larger than 0.2. Remember, however, that the data are noisy, and the error bar, which is very hard to estimate in this composite, may also be as large as 0.15. We looked at the dependence on shear across the inversion zone, but the vertical resolution of the wind data is poor, and we could find none.

When the influence of surface wind shear is added to the entrainment parameterization, [*Stull*, 1976, 1988, *Tennekes and Driedonks*, 1981), equation (1) can be rewritten as

$$F_{i\theta v} = -\gamma_1 F_{s\theta v} - (\gamma_2 \rho c_p T_0/(g z_i))\, u_*^3 \qquad (7)$$

where $z_i = -\Delta P_i/(\rho g)$ and u_* ($m\ s^{-1}$) is the friction velocity. The parameter γ_1 in (7) may be regarded as an asyomptotic value of A_R in (1) for low wind speed, when $u_* \to 0$. We related u_* to the BL wind speed u_z, assuming a stability-corrected logarithmic wind profile:

Table 1. Revised Fluxes from Boundary Layer and Inversion Layer Budgets for Time Period 1400-2130 UTC

	Surface			Inversion						A_R	
				BL Budget			IL Budget			BL Budget	IL Budget
IFC	$F_{s\theta}$	F_{sq}	$F_{s\theta v}$	$F_{i\theta}$	F_{iq}	$F_{i\theta v}$	$F_{i\theta}$	F_{iq}	$F_{i\theta v}$		
-2	90	325	113	-80	369	-54	-60	266	-42	0.48	0.37
-3	120	282	140	-130	363	-104	-71	386	-44	0 74	0 31
-4	233	52	236	-68	101	-60	-63	147	-52	0.26	0.22
All	142	232	159	-100	295	-80	-66	291	-45	0.50	0.29

BL, boundary layer. IL, inversion layer. IFC, intensive field campaign. Mean A_R is 0.39 ±0.19.

$$u_* = u_z / [k(\ln(z/z_o) - \psi_m(z/L))]^{-1} \quad (8)$$

where k is von Karman's constant (0.4), z_o (in meters) is the roughness length for momentum, ψ_m is the stability correction for momentum, and L (in meters) is the Monin-Obukhov length. We assumed that the logarithmic wind profile extended to $z = 0.2 z_i$, and set $u_z = \overline{V}$ (the mean BL wind speed in Table 2) at that level. The value for ψ_m was estimated from the classic *Dyer and Hicks* [1970] formulation, and z_o for the FIFE site was set to 0.19 m [*Betts and Beljaars*, 1993]. The value for L was estimated as

$$L = -\rho c_p T u_*^3 / (kgF_{s\theta}) \quad (9)$$

where $F_{s\theta}$ was the surface measurement.

The estimates for A_R in Table 2 correspond to γ_1 values in equation.. 7 of 0.42 (BL budget), 0.21 (IL budget), and 0.31 (mean budget) and γ_2 values of 0.8 (BL budget) and 0 7 (IL and mean budgets). Although A_R was very sensitive to the budgeting method, the increase in A_R with wind speed was consistent between the BL and IL budgets. The result was a large difference in γ_1 but a consistent $\gamma_2 \approx 0.75$. This value for γ_2 lay just below the lower limit of previous estimates which ranged from 1 0 [*Moeng and Sullivan*, 1994] to 5.0 [*Driedonks*, 1981] and 6.0 [*Stull*, 1976, 1988]. The IL budget estimate for γ_1 compared closely with the accepted value of 0.20 [*Stull*, 1988, *Moeng and Sullivan*, 1994], but our value is likely to be an underestimate, since the IL budget method neglects subsidence at BL top.

Table 3 shows the dependence on time of day for all the sonde pairs between 1400 and 2230 UTC. The noisiness of the data is a little more apparent. We have included here the last time period shortly before sunset, which we excluded from the earlier averages because the last sonde often shows signs of stabilization as the surface cools. The wide difference between the estimates of $F_{i\theta v}$ for this time period 2130-2300 is apparent There is some suggestion that A_R is large in the early morning and falls to a minimum near local noon (1830 UTC), as we also saw in the work of *Barr et al.* (submitted manuscript, 1996). In the late afternoon the noise in the BL budget values of $F_{i\theta v}$ is apparent. Once again it is hard to give an accurate error estimate.

3. Conclusion

This paper revisits the sonde budget estimates of entrainment of BB94, using an averaging method which removes a small bias that we have noticed in our earlier sonde composite approach. We get a mean value for the entrainment parameter $A_R = 0.39 \pm 0.19$, which is 10% smaller than the previous one but still high We also note that the dependence of entrainment on wind speed seems quite marked in the data. When we account in more detail for the increase of entrainment with windspeed, we get a mean

Table 2. A_R as a function of wind speed

Wind Speed Class ms^{-1}	$\overline{V}$ m s^{-1}	Number of Pairs	A_R		
			BL Budget	IL Budget	Mean
<5	3.1	40	0.43	0.22	0.32
5-10	7.0	47	0 48	0.29	0.38
>10	12 4	48	0.59	0.35	0.47

See Table 1 for definition of terms. Uncertain error estimate ±0.15

Table 3. Inversion level fluxes and entrainment by time of day

Time Block, UTC	Surface			Inversion						A_R		
				From BL Budget			From IL Budget					
	$F_{s\theta}$	F_{sq}	$F_{s\theta v}$	$F_{i\theta}$	F_{iq}	$F_{i\theta v}$	$F_{i\theta}$	F_{iq}	$F_{i\theta v}$	BL	IL	Mean
1400-1530	108	143	118	-70	171	-58	-79	336	-55	0.49	0.47	0.48
1530-1700	157	236	173	-104	310	-82	-70	321	-47	0.47	0.27	0.37
1730-1800	174	275	194	-101	349	-76	-47	260	-29	0.39	0.15	0.27
1830-2000	161	285	181	-100	365	-74	-70	307	-48	0.41	0.27	0.34
2000-2130	119	241	135	-135	310	-114	-60	217	-45	0.84	0.33	0.58
2130-2300	59	186	72	-16	246	1	-64	208	-49	...	0.68	...

See Table 1 for definition of terms. Uncertain error estimate, ±0.15.

asymptotic free convective value of A_R of 0.31, compared with the commonly accepted value of 0.2. Our FIFE estimates are, however, higher than those from a similar study over the Boreal forest, and for this discrepancy we have no explanation.

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