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Inferring regional surface fluxes from convective boundary layer characteristics in a Sahelian environment

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Abstract. Regional scale fluxes of sensible heat, latent heat, and CO_2 are estimated by means of a method which involves the heat and mass budget of the convective boundary layer (CBL). This method is based upon an integrated form of the conservation equation for a given scalar and is used with radiosounding data collected during several clear days of measurements of the Hydrological Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) at the end of the rainy season and the beginning of the dry season in 1992. The regional estimates of sensible heat flux provide plausible results. For latent heat flux, only 4 days out of 8 give satisfactory agreement, and the introduction of a correction for advection does not improve the agreement for the rest of the days. For CO_2 flux calculation the method used links regional fluxes to concentrations measured within the surface layer. The estimates obtained for the CO_2 uptake at a regional scale differ from those measured on a fallow savannah, but the overall trend (a decrease of the CO_2 uptake due to soil water depletion and vegetation drying out) is respected. Our general conclusion is that the CBL budget method can work to estimate sensible heat flux, but it is very hazardous to estimate latent heat flux and CO_2 uptake.

1. Introduction

The convective boundary layer (CBL) consists of a progressively growing layer of strong convective turbulence, which moves across the land surface in response to the mean wind field. Its properties change by incorporating surface fluxes (sensible heat, water vapor, carbon dioxide) and overlying air into itself. This kind of change occurs in most fair-weather conditions but not when the atmosphere is disturbed by fronts, by deep cumulus convection, or by storms [*Raupach*, 1992]. The CBL acts as a large natural integrator of patch-scale surface heterogeneities. Its characteristics can be used to infer regional surface fluxes of mass and energy over heterogeneous terrain, which represents a key issue in our understanding of land surface-atmosphere interactions.

There exist two main approaches for evaluating regionally averaged surface fluxes of scalar entities from properties of the CBL. One uses similarity theory and infers surface fluxes from flux-gradient relationships [*Abdulmumin et al.*, 1987; *Brutsaert and Sugita*, 1991]. Surface roughness and surface concentrations must be specified together with wind velocity. The other approach uses the daytime CBL as a semiclosed region and is based upon conservation equations for scalar entities. These equations, which describe the overall behavior of the CBL, have been examined and used by several authors [*McNaughton and Spriggs*, 1986; *McNaughton*, 1989; *Hipps et al.*, 1994]. *Munley and Hipps* [1991] compared the two approaches and concluded that the one involving conservation equations have a more sound basis than similarity approaches and produced better evaporation estimates. *Diak and Whipple* [1994] made accurate estimates of the regional daytime fluxes of sensible and latent heat using the time change of the height of the CBL interpreted by a surface layer-mixed layer model.

In this paper the second method, i.e., the CBL budget approach, is used to link surface fluxes at regional scale to the atmospheric characteristics measured by radiosoundings. The experimental data come from the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel). A previous study on the Sahelian convective boundary layer and the prediction of its growth has been carried out by *Culf* [1992]. HAPEX-Sahel [*Goutorbe et al.*, 1994; *Prince et al.*, 1995] was a coordinated experiment of field measurements, aiming at a better understanding of biosphere-atmosphere exchange processes at different scales of space and time, in a semiarid environment. Its main objective was to bridge the gap between the local and the general circulation model (GCM) grid box scale. The Sahelian environment is characterized by a highly variable rainfall, much less than potential evaporation, which results in a very sparse vegetation cover and highly intermittent streamflow. Within this context the paper examines the possibilities of determining sensible and latent heat regional fluxes from the atmospheric profiles of temperature and humidity. It also intends to infer CO_2 surface flux from concentration measurements made within the surface layer and from the heights of the CBL.

2. Theoretical Aspects

2.1. Integral Form of the CBL Budget Equation

The CBL comprises a relatively thin surface layer, where the gradients of scalar entities may be significant, and a well-mixed

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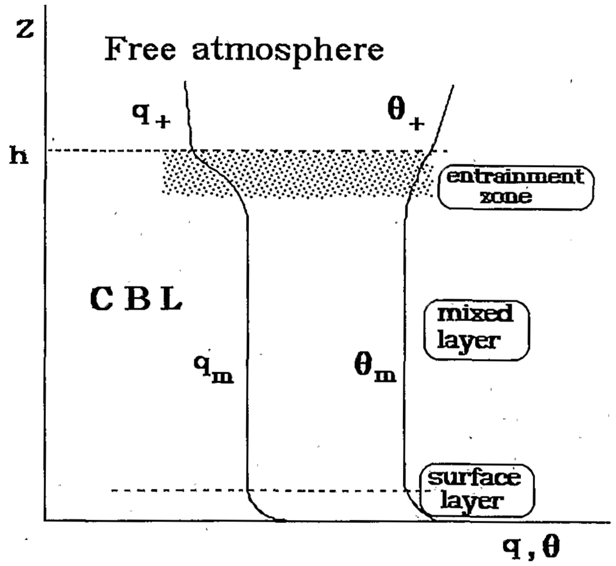

Figure 1. Idealized vertical profiles of potential temperature (θ) and specific humidity (q) obtained from a radiosounding, and visualization of the inversion height (h), taken as the top of the entrainment zone.

layer. Above the capping inversion of the mixed layer is the free atmosphere, whose properties are determined by synoptic scale processes. Figure 1 gives the schematic structure of potential temperature and specific humidity profiles through the convective boundary layer. In the absence of subsidence the conservation equation for a given scalar is classically written as [*McNaughton and Spriggs*, 1986]

$$h\frac{dC_m}{dt} = F_c + (C_+ - C_m)\frac{dh}{dt} \tag{1}$$

where C_m is the scalar concentration of the well-mixed layer, h is the CBL depth, C_+ is the scalar concentration in the undisturbed atmosphere, just above the capping inversion, and F_c is the surface flux. Equation (1) can be rearranged in terms of the derivative of the product hC_m

$$d(hC_m) = F_c\,dt + C_+\,dh \tag{2}$$

By integrating (2) between an initial time t_1, when $C_m = C_{m1}$, $C_+ = C_{+1}$, and $h = h_1$, and a time $t_2(C_{m2}, C_{+2}, h_2)$, one obtains the integral form of the CBL budget [*McNaughton and Spriggs*, 1986]

$$I_c = \int_{t_1}^{t_2} F_c(t)\,dt = h_2C_{m2} - h_1C_{m1} - \int_{h_1}^{h_2} C_+(h)\,dh \tag{3}$$

where I_c is the cumulative surface flux between t_1 and t_2.

Above the CBL the atmosphere is stably stratified. Potential temperature increases more or less linearly with height with a constant gradient of around 5°K km^{-1}. Also, the humidity gradient above the CBL is often considered to be constant [*Raupach*, 1991]. As a first approximation, we can assume a linear variation of C_+ with h. In this case the integral of the right-hand member of (3) can be evaluated simply as

$$\int_{h_1}^{h_2} C_+(h)\,dh = (h_2 - h_1)(C_{+2} + C_{+1})/2 \tag{4}$$

And (3) can be rewritten as

$$I_c = h_2(C_{m2} - C_+) - h_1(C_{m1} - C_+) \tag{5}$$

where C_+ is defined as the mean value of C_{+1} and C_{+2}, $C_+ = (C_{+1} + C_{+2})/2$. *McNaughton* [1989] proposed a similar formula to estimate the drawdown in CO$_2$ during the convective hours of the day. If t_1 is chosen as the time when $C_m = C_+$, (5) simplifies into the equation given by *Raupach et al.* [1992]

$$I_c(t) = h(t)[C_m(t) - C_+] \tag{6}$$

It should be noted that (3) and (5) do not account for any effects due to large scale advection or subsidence. *Hipps et al.* [1994] subtracted from the right-hand member of (3) and (5) an explicit term A describing horizontal advection. Its calculation is based upon the assumption that advection is constant throughout the CBL and related to the temporal change, between t_1 and t_2, of the scalar concentration in the layer of air just above the CBL at the height h_2. If this concentration passes from $C_{+2}(t_1)$ to $C_{+2}(t_2)$, the term A is written as

$$A = \int_{C_{+2}(t_1)}^{C_{+2}(t_2)} h(C_{+2})\,dC_{+2} \tag{7}$$

Assuming a linear variation of h as a function of C_{+2} and putting $\Delta C_{+2} = C_{+2}(t_2) - C_{+2}(t_1)$, A can be evaluated as

$$A = \Delta C_{+2}\cdot(h_1 + h_2)/2 \tag{8}$$

Equations (5) and (8) will be used to evaluate the time-integrated flux of sensible heat and water vapor from radiosound measurements. For sensible heat, C stands for $\rho c_p\theta$, where ρ is air density, c_p is the specific heat of air at constant pressure, and θ is the potential temperature. For water vapor, C must be substituted by ρq, where q is the specific humidity of air.

2.2. CBL Budget Equation Involving Surface Concentrations

Very often the height where concentration measurements are made is located within the surface layer. Consequently, a correction is required to account for the concentration difference between the measurement height (C_s) and the well-mixed layer (C_m). *Raupach et al.* [1992] developed a correction based upon the rough approximation $I_c \approx F_c(t_2 - t_1)$, and the flux-gradient relationship $F_c = (C_s - C_m)/r_a$, where r_a is the aerodynamic resistance between the measurement height and a height within the well-mixed layer. Combining these two relationships leads to $C_m = C_s - I_cr_a/(t_2 - t_1)$, which, subsituted in (3), yields

$$I_c = \frac{h_2C_{s2} - h_1C_{s1} - \int_{h_1}^{h_2} C_+(h)\,dh}{1 + r_a(h_2 - h_1)/(t_2 - t_1)} \tag{9}$$

Replacing the integral by the approximate value given by (4) yields

$$I_c = \frac{h_2[C_{s2} - C_+] - h_1[C_{s1} - C_+]}{1 + r_a(h_2 - h_1)/(t_2 - t_1)} \tag{10}$$

where C_+ is the mean concentration just above the CBL $(C_{+1} + C_{+2})/2$.

The aerodynamic resistance r_a between a height z_1 within the surface layer, at which concentration is measured, and a height z_2 within the well-mixed layer (say $z_2 = 100$ m) is calculated from surface layer similarity theory and written as [*Brutsaert*, 1984]

$$r_a = \frac{1}{ku^*}\left\{\ln\left(\frac{z_2 - d}{z_1 - d}\right) - [\Psi_H(\zeta_2) - \Psi_H(\zeta_1)]\right\} \qquad (11)$$

where k is the von Karman constant (0.4), u^* is the friction velocity, and d is the zero plane displacement height. Ψ_H is the integral diabatic function for heat and mass in unstable conditions as given by *Dyer* [1974]

$$\Psi_H(\zeta) = 2\ln\left[\frac{1 + (1 - 16\zeta)^{1/2}}{2}\right] \qquad (12)$$

with $\zeta = (z - d)/L$, a dimensionless parameter and a function of the Monin-Obukhov length L, defined as $L = -(u^{*3}\rho c_p T_a)/(kgH)$, where g is the acceleration of gravity, H is sensible heat flux, and T_a is air temperature in Kelvins. The friction velocity is calculated by an iteration process, from the wind speed u at a given height z above the surface, with the expression

$$u^* = \frac{ku}{\ln[(z - d)/z_0] - \Psi_M(\zeta)} \qquad (13)$$

where $\Psi_M(\zeta)$ is the stability function for momentum and z_0 is the roughness length.

Equations (10) and (11) will be used to determine the time-integrated CO_2 flux from measurements of the CBL heights (h_1 and h_2) and measurements of the corresponding concentrations within the surface layer (C_{s1} and C_{s2}). The CO_2 concentration profile in the free atmosphere (C_+), just above the CBL, will be assumed to be constant [*Raupach et al.*, 1992].

3. Methods

3.1. Site Description

The vegetation within the 1° × 1° experimental area of HAPEX-Sahel is typical of the southern Sahelian zone with three main types [*Goutorbe et al.*, 1994]: millet fields, fallow savannah, and tiger bush. Millet is a sparse crop sowed at the beginning of the rainy season and grown without irrigation. The fallow savannah consists of woody shrubs of *Guiera senegalensis* scattered above a sparse annual herbaceous cover. The tiger bush (sparse dryland forest) only occurs on the laterite plateaux. It is characterized by dense strips of vegetation, made of woody perennials and trees, separated by areas of completely bare soil. The proportion of each vegetation within the square degree is about 30% for the tiger bush, 40% for the fallow savannah, and 30% for the millet fields [*Prince et al.*, 1995]. The measurements used in this study were made during the IOP (intensive observation period) of the HAPEX-Sahel experiment, from August to October 1992, which encompasses the end of the rainy season and the start of the dry season.

3.2. Determination of CBL Characteristics

The radiosoundings were performed by the CNRM (Centre National de Recherche Météorologique) of France from facilities installed in Hamdallaye (east of Niamey). Digicora equipments, manufactured by Vaisala (Helsinki, Finland), were used in conjunction with RS80 radiosondes measuring pressure, temperature, and humidity [*Bergue and Bessemoulin*, 1993]. The sounding program began August 21, 1992, and ended October 12. For 20 days during this period the radiosoundings were performed every 2 hours, generally from 0500 to 1700 UT. Among these 20 days, 8 days were selected on the basis of the following criteria: (1) The incoming solar radiation R_s must be high enough to allow a good development of the CBL; (2) The wind direction must not change too much during the daytime; if not, the data are not representative of the same region and lead to bad estimates (see day of year (DOY) 277 as an example); and (3) the days selected must cover more or less the entire period of measurement to capture the evolution of wetness conditions.

The inversion height, which defines the top of the CBL, was graphically determined from the profiles of potential temperature (θ) and specific humidity (q) plotted versus height (z) (Figure 1). The inversion height (h) was located at the top of the entrainment zone, as visualized in Figure 2. The concentration within the well-mixed layer (C_m) was calculated as the mean value of all the data points below the inversion height, and the concentration just above the inversion height (C_+) was determined as the mean value of the first three data points above h [*Raupach et al.*, 1992]. At each level of the radiosounding, the value of ρ is calculated from temperature (T) and pressure (p) by means of the gas law ($\rho = 0.0035p/T$ in SI units).

3.3. Surface Measurements

The estimates of regional surface fluxes are compared to surface measurements made at the east central site of the HAPEX-Sahel square degree [*Goutorbe et al.*, 1994]. This site is located at about 15 km east of Hamdallaye, where the radiosoundings were performed. Surface fluxes of sensible and latent heat were measured on millet and fallow savannah by the energy balance-Bowen ratio technique [*Monteny et al.*, 1997]. The CO_2 flux was determined on fallow savannah by means of the same method. To measure the CO_2 gradient, air was sampled by two pumps at the same two heights as the temperatures and air moistures and drawn via buried copper tubes to the gas analyzer (infrared gas analyzer (IRGA), model III, Analytical Development Company (ADC) Ltd., England). The zero drift of the gas analyzer was continuously monitored by drawing a known CO_2 concentration in the sample cells to give a zero reading. From another mast, air was sampled at a height of 12 m, and CO_2 concentration was measured by a second gas analyzer and recorded [*Monteny et al.*, 1997]. The CO_2 concentrations are expressed in a mole fraction (ppm). They have to be multiplied by 1.79 at the temperature of 30°C to obtain concentrations in kg m^{-3}. To calculate the CO_2 regional flux from (10), C_+, just above the CBL, was taken as constant and determined by adjustment as explained below. The aerodynamic resistance r_a was calculated from (11) with $d = 1.4$ m and $z_0 = 0.25$ m. These values were determined on fallow savannah following *Choudhury and Monteith* [1988], who fitted simple functions to the curves obtained by *Shaw and Pereira* [1982] from second-order closure theory [*Troufleau et al.*, 1997]. The wind velocity on fallow savannah was measured at the same height of 12 m, where air was sampled.

4. Results and Discussion

4.1. Sensible and Latent Heat Fluxes

The cumulative fluxes of sensible heat and water vapor were calculated following (5) for the 8 days selected: August 21 (DOY 234), August 29 (DOY 242), September 6 (DOY 250),

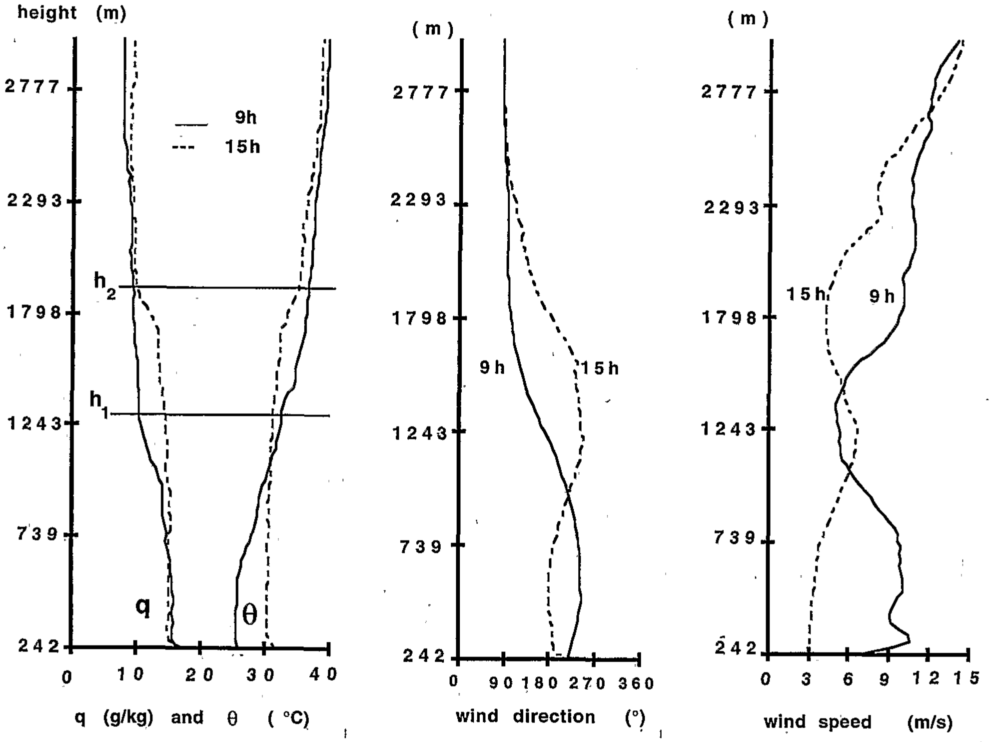

Figure 2. For a typical day of the rainy season, day of year (DOY) 242 (August 29, 1992), vertical profiles of potential temperature (θ), specific humidity (q), wind direction, and wind velocity at the soundings of 0900 and 1500 UT.

September 9 (DOY 253), September 17 (DOY 261), September 25 (DOY 269), October 3 (DOY 277), and October 8 (DOY 282). Two radiosoundings were used, one in the morning at 0900 UT and one in the afternoon at about 1500 UT. Table 1 lists the height of the CBL, the mean concentrations of heat ($C_H = \rho c_p \theta$) and water vapor ($C_W = \rho q$) within and just above the CBL, and the mean wind speed and the mean wind direction within the CBL for the two radiosoundings of each day of measurement. Tables 2 and 3 list the regional estimates of sensible and latent heat fluxes. H_r and λE_r are the fluxes calculated by (5). H'_r and $\lambda E'_r$ are the fluxes calculated by the same equation, taking into account the advective term (equation (8)) introduced by *Hipps et al.* [1994]. The surface fluxes measured by the Bowen ratio system on two of the three types of vegetation encountered on the site (millet field and fallow savannah) are also listed. These fluxes, denoted by subscripts millet and fallow, are calculated as the average of 20 min values over the period between the two radiosoundings (t_1 and t_2). They are directly comparable to the regional estimates obtained from the radiosoundings. For the sake of comparing

Table 1. Measurements for the Two Radiosoundings at t_1 and t_2 of Each Day

Day of Year	Time, UT	h, m	C_{Hm}, kJ m^{-3}	C_{H+}, kJ m^{-3}	C_{Wm}, g m^{-3}	C_{W+}, g m^{-3}	U, m s^{-1}	D, deg
234	0900	1466	34.2	37.4	16.5	9.5	10.4	254
	1500	1954	36.6	38.7	15.1	7.2	8.1	281
242	0900	1272	31.1	34.2	15.7	10.7	8.2	219
	1500	1883	33.3	34.4	15.3	9.5	4.6	206
250	0900	1581	34.1	34.8	13.1	10.9	7.8	222
	1530	1959	35.9	35.3	13.9	9.5	···	···
253	0900	617	35.1	37.5	16.6	11.4	3.2	278
	1500	1229	38.6	37.1	8.9	5.7	3.8	17
261	0900	1268	34.5	37.4	12.5	4.6	···	···
	1500	1919	37.2	36.5	9.7	4.0	5.1	27
269	0900	1319	36.4	38.7	11.7	4.6	3.2	247
	1500	2181	39.2	37.9	9.1	4.4	5.1	334
277	0900	1056	35.7	36.4	12.8	7.8	4.7	224
	1500	2748	36.3	33.9	9.0	5.6	2.0	11
282	0900	1241	35.8	39.7	11.2	4.2	···	···
	1500	2271	38.3	36.6	8.4	3.6	3.9	144

Height (h) of the convective boundary layer (CBL), mean concentrations of heat ($C_H = \rho c_p \theta$) and water vapor ($C_W = \rho q$) within the CBL (subscript m) and just above the inversion height (subscript +), and mean wind speed (U) and mean wind direction (D) within the CBL.

the regional estimates we also listed the mean incoming solar radiation R_s (between t_1 and t_2) and the mean surface fluxes (denoted by subscript mf) calculated over the instrumented patches (millet plus fallow), which represent 70% of the whole area. These mean fluxes are calculated as $F_{mf} = 0.43\ F_{\text{millet}} + 0.57\ F_{\text{fallow}}$ (with $F = H$ or λE) to account for the relative area of both patches.

It is difficult to use the surface fluxes as ground truth since they are not completely representative of the area covered by the CBL (only two point measurements). However, the regional estimates of sensible heat flux listed in Table 2 seem to be plausible. As the temporal change in potential temperature above the CBL is rather small ($\Delta C_{+2} \approx 0$), the advective term A (equation (8)) does not substantially alter the results. The regional estimates of latent heat flux inferred from the conservation equation are not as good as for sensible heat. For 1 day (DOY 253) the estimated value is of the wrong sign, and for 3 other days (DOY 261, 269, and 277) the estimates are manifestly too low. During DOY 253 the average wind direction within the CBL in the afternoon is north, which could explain a strong advection effect coming from the north, where the air mass is much drier than over the measurement area. Nevertheless, the advection-corrected flux is still negative. Apparently, the advection term A does not improve the results since for DOY 269 and 277 the advection-corrected estimates of latent heat flux are negative instead of positive without correction. Figure 3 exemplifies, for DOY 277, the change in wind direction between 0900 and 1500 UT (the change in air water content results from the advection of drier air coming from the north) and the corresponding change in the specific humidity profiles. In the morning the mean wind direction is south, whereas it is north in the afternoon. This day is typical of the conditions prevailing during the southward shift of the Intertropical Convergence Zone (ITCZ), when two distinct air masses are superposed.

The determination of the inversion heights h_1 and h_2, which appear in the cumulative flux I_c given by (5), is not always a simple procedure. Since they are determined graphically, a certain guess is sometimes necessary, and large errors can be made on their values, which make them the controlling uncertainty in the calculation of the cumulative flux of heat or water vapor. It is the reason why the sensitivity of the cumulative flux I_c to errors made on the determination of the inversion heights has been assessed. By deriving I_c (equation (5)) with respect to h_2 and h_1 we obtain

$$\delta I_c = |C_{m2} - C_+|\delta h_2 + |C_+ - C_{m1}|\delta h_1 \tag{14}$$

Table 2. Regional Estimates and Mean Surface Values of Sensible Heat Flux (Between t_1 = 0900 UT and t_2 = 1500 UT)

Day of Year	H_r	H_r'	H_{millet}	H_{fallow}	H_{mf}	R_s
234	136	127	113	247	189	780
242	99	120	88	129	111	839
250	139	137	93	135	117	876
253	134	123	113	67	87	879
261	171	171	184	93	132	904
269	213	219	···	123	···	845
277	113	98	210	161	182	848
282	146	171	225	267	249	857

Here H_r is calculated from (5), H_r' is calculated from (5), with the advective term introduced by *Hipps et al.* [1994] (equation (8)), and H_{mf} is the mean surface flux over the instrumented area (millet plus fallow). R_s is the incoming solar radiation measured close to the site of the radiosoundings. All the values are in W m^{-2}.

Table 3. Regional Estimates and Mean Surface Values of Latent Heat Flux (Between t_1 = 0900 UT and t_2 = 1500 UT)

Day of Year	λE_r	$\lambda E_r'$	$\lambda E_{\text{millet}}$	$\lambda E_{\text{fallow}}$	λE_{mf}	R_s
234	141	145	167	117	139	780
242	312	221	326	321	323	839
250	300	363	256	296	279	876
253	−225	−102	281	372	333	879
261	7	17	256	405	341	904
269	53	−271	···	318	···	845
277	3	−152	164	221	196	848
282	127	74	137	159	150	857

Here λE_r is calculated from (5), $\lambda E_r'$ is calculated from (5), with the advective term introduced by *Hipps et al.* [1994] (equation (8)), and λE_{mf} is the mean surface flux over the instrumented area (millet plus fallow). R_s is the incoming solar radiation. All the values are in W m^{-2}.

We consider the following conditions: h_1 = 1000 m at t_1 = 0900 UT, h_2 = 2000 m at t_2 = 1500 UT, ρq_{m2} = 9 g m^{-3}, ρq_{m1} = 12 g m^{-3}, and ρq_+ = 3 g m^{-3}. These data, which are typical of a clear day of the wet season in the Sahelian environment, lead to an average evaporation of 340 W m^{-2} between t_1 and t_2. The relative error on the cumulative flux I_c is about 15% for an error of 30 m on h_1 and h_2 (30 m corresponds to the average distance between two heights of measurement in a radiosounding). Since it is often difficult to determine graphically the inversion heights with a precision better than 60 m, one cannot expect to have a relative error on I_c less than 30%.

It is worthwhile pointing out that it is not interesting to use (5) on too short a period (say 2 hours, the sondes being released every 2 hours), because of the uncertainty on the inversion heights as well as on the temperature and humidity profiles. Since these uncertainties are the same whatever the radiosounding, it is better to minimize the relative error on $I_c(\delta I_c/I_c)$ by maximizing the cumulative flux, i.e., the time between two radiosoundings.

4.2. CO$_2$ Flux

The cumulative uptake of CO$_2$ was determined by means of (10) and (11). The CBL and surface layer characteristics needed to calculate this cumulative uptake are listed in Table 4 for several days selected on the basis of the availability of CO$_2$ concentration measurements. The cumulative fluxes are calculated between t_1 = 1100 UT and t_2 = 1500 UT (instead of t_1 = 0900 UT) for the reason explained hereafter. The values of the cumulative uptake calculated from t_1 = 0900 UT did not give plausible results. We assumed that it was due to the fact that the surface concentration C_s in the morning can be greater than the mixed layer concentration C_m because of the nocturnal accumulation of CO$_2$ within the surface layer, due to plant and soil respiration (and also fires from surrounding villages). This situation leads to a flux oriented upward between the level of measurement and the mixed layer, whereas it is oriented downward between the level of measurement and the surface due to photosynthesis. In this case, there is a breakdown of (10), which is no longer valid. By considering

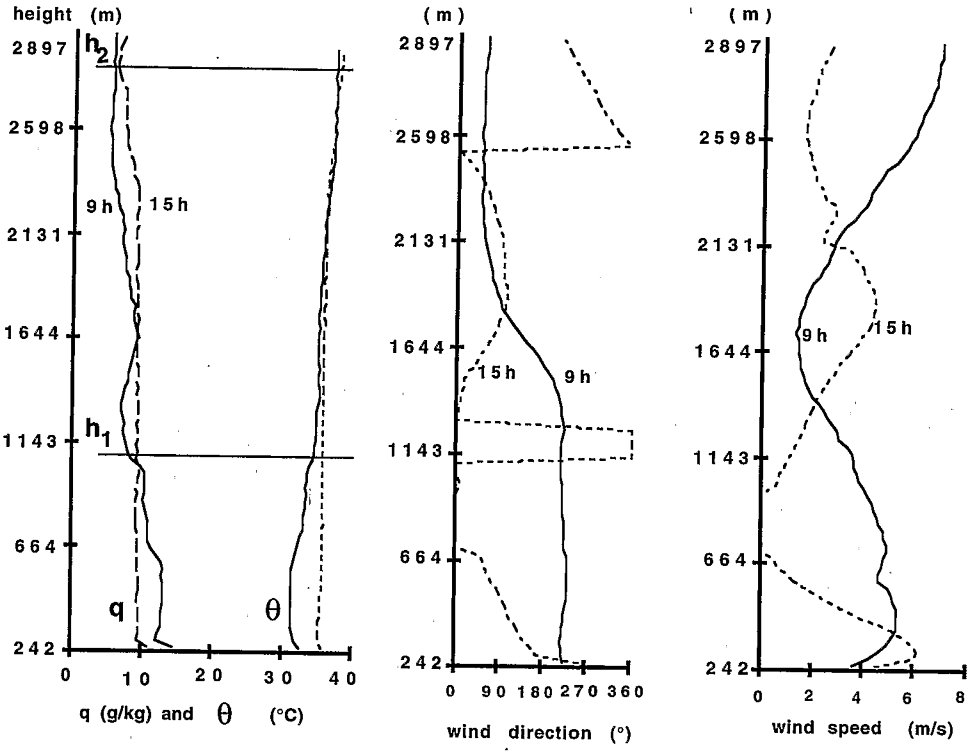

Figure 3. For a day with large scale advection, DOY 277 (October 3, 1992), vertical profiles of potential temperature (θ), specific humidity (q), wind direction, and wind velocity at the soundings of 0900 and 1500 UT.

the surface concentration at t_1 = 1100 UT we are sure that this case does not occur and that the CO_2 flux is conservative between the vegetation and the bottom of the well-mixed layer.

To calculate I_c from (10), the value of C_+ is needed. Since this value was not measured and is a priori unknown, it was inferred by minimizing the root mean square error (RMSE) between the calculated values of I_c and the values measured on fallow savannah for the 5 days available. The value obtained, and used to calculate the estimates of I_c listed in Table 5, was 325 ppm. The sensitivity of the cumulative assimilation flux I_c to variation or uncertainty on C_+ can be assessed by deriving (10) with respect to C_+

$$\delta I_c = -\left(\frac{1}{h_2 - h_1} + \frac{r_a}{t_2 - t_1}\right)^{-1} \delta C_+ \qquad (15)$$

Table 4. Characteristics of the CBL and of the Surface Layer Used to Estimate CO_2 Uptake

Day of Year	h_1, m	h_2, m	C_{s1}, ppm	C_{s2}, ppm	r_a, s m^{-1}
261	1480	1919	334	320	4.5
269	1407	2181	336	330	3.9
270	1656	1950	336	329	3.9
272	1227	2130	332	328	3.9
274	1942	2620	333	328	3.4
277	1313	2748	332	329	3.4
281	1168	2830	337	331	3.3

Here h_1 and h_2 are the height of the CBL at t_1 = 1100 UT and t_2 = 1500 UT. C_{s1} and C_{s2} are the CO_2 concentrations at a height of 12 m at t_1 and t_2. Calculated by (11), r_a is the aerodynamic resistance between z_1 = 12 m and z_2 = 100 m.

Assuming the same conditions as for latent heat with C_{s1} = 335 ppm, C_{s2} = 325 ppm, C_+ = 330 ppm, and r_a = 5 s m^{-1}, I_c is equal to −22 g m^{-2}, and an increase of 1 ppm on C_+ leads to a decrease of 1.5 g m^{-2} on I_c, which represents about 7%. So I_c is relatively sensitive to C_+ value.

The results listed in Table 5 show a decrease of CO_2 regional uptake parallel to soil drying out and green vegetation leaf area index (LAI) decreasing. For the last 2 days of the sample the flux of CO_2 is positive, which means that the assimilation rate is so low that it is exceeded by the respiration rate. The matching between regional estimates and fluxes measured on fallow savannah is not very good, but we do not know if the latter are really representative of fluxes at regional scale.

Table 5. Regional Estimates of CO_2 Uptake, $I_{c,r}$, Integrated From t_1 = 1100 UT to t_2 = 1500 UT, Following (10), and Surface Values Measured on Fallow Savannah, $I_{c,\text{fallow}}$

Day of Year	$I_{c,r}$, g m^{-2}	$I_{c,\text{fallow}}$, g m^{-2}	LAI$_{\text{millet}}$	S_{millet}, mm	LAI$_{\text{fallow}}$	S_{fallow}, mm
261	−36	−2.6	2.3	61	0.5	75
269	−6.8	−5.1	1.5	39	0.7	51
270	−17	···	···	···	···	···
272	−3.2	···	···	31	···	46
274	−12	−3.4	1.4	27	0.95	40
277	2.4	−3.4	···	···	···	···
281	3.8	0.2	0.9	21	0.4	32

The leaf area index (LAI) and the water content S in the soil layer 0–60 cm, measured on a millet field and on the grass layer of a fallow savannah, are also listed. C_+ has been set as 325 ppm.

5. Conclusion

The CBL budget method, based upon a simplified form of the integrated scalar conservation equation, provides simple equations which can be used in theory to estimate surface fluxes at regional scale from radiosounding data. In practice, the results obtained with data collected in the Sahelian zone are not really convincing, which challenges the effectiveness of the approach. Our specific evaluation is as follows.

1. For sensible heat and the 8 days selected the CBL method gives plausible values. For water vapor the cumulative fluxes appear to be correct only for 50% of the days of measurement. Since these experimental results concern 8 days selected out of 20 with criteria aiming at choosing the best conditions to apply the CBL budget method, it is rather disappointing to find such a poor agreement between regional estimates and surface fluxes for latent heat flux.

The following reason can be advanced to explain why the CBL budget method works better with sensible heat flux than with latent heat flux. Experimentally, the temperature profile into the well-mixed layer appears to be more frequently vertical than the humidity profile. That means that the well-mixed layer is better mixed for temperature than for humidity. It is certainly due to the fact that in the case of temperature, there is a positive heat flux into the mixed layer both at the top and at the surface, whereas in the case of humidity the water vapor flux goes upward at both limits. So it is much easier for convective mixing to maintain a vertical profile of temperature than a vertical profile of humidity [*de Bruin*, 1989]. Since the CBL method is based upon the assumption of a well-mixed layer (i.e., vertical profiles), this difference can explain why the method works better for sensible heat than for latent heat.

2. The advection term introduced by *Hipps et al.* [1994], represented by (7) and (8), generally does not improve the estimates of surface fluxes of sensible and latent heat. And in the specific conditions of the Sahelian zone, caution is recommended when the ITCZ shifts southward, leading to the superposition of two air masses with different characteristics. The CBL budget method does not apply in this case.

3. The calculated regional CO_2 uptakes exhibit a decrease which follows the vegetation drying out. Although they are fairly different from those measured on fallow savannah, it is hazardous to draw general conclusions, given the poor representativeness of only one point of surface measurement and the way the CO_2 concentration above the CBL has been determined. Nevertheless, the derivation of (10), used to calculate the cumulative uptake I_c of CO_2 and obtained from the crude assumption of a constant flux F_c between t_1 and t_2 (related to I_c by $I_c \approx F_c(t_2 - t_1)$), is certainly questionable. We have to note also that the CBL approach is difficult to apply in practice to the CO_2 uptake because the CO_2 concentration just above the CBL (C_+) is generally not measured by radiosounding.

The relative simplicity of the CBL budget equations and the great interest of estimating surface fluxes at regional scale make the CBL method appealing. However, the results obtained with this particular data set are not very encouraging. Our general conclusion is that the method can work to estimate sensible heat flux, but it is very hazardous to estimate latent heat flux. The CBL approach is not very convincing either, concerning CO_2 uptake.

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