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# THE ENTRAINMENT PROCESS OF CARBON DIOXIDE IN THE ATMOSPHERIC BOUNDARY LAYER


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## 1. INTRODUCTION

The atmospheric boundary layer (ABL) is the region where the air masses influenced by the surface processes interact with the air that originated from the free troposphere. The exchange and mixing of these air masses take mainly place in a thin layer known as entrainment zone. Under convective conditions this zone is characterized by a strong density interface (Stull, 1988; Garratt, 1992). Depending on the variable under study, the entrained air has a different impact on its distribution and evolution. For heat, the entrainment flux across the layer acts as an additional source next to the surface flux and consequently warms up the CBL (convective boundary layer). With respect to water vapor, the free tropospheric air entrained in the boundary layer is characterized by a lower moisture content and consequently it dries the CBL. With regard to carbon dioxide ($CO_2$), the air entrained from the residual layer or the free troposphere down into the boundary layer can have different $CO_2$ concentration, meaning that entrainment can act as either a source or a sink next to the surface biospheric processes of photosynthesis, respiration and microbial decay.

In this study, we use aircraft observations made over the meteorological tower at Cabauw (The Netherlands) in order to study the role of entrainment in the evolution and distribution of $CO_2$ in the CBL. These upper air measurements are supplemented with surface and remote sensing measurements taken simultaneously during the experiment. We focus our study on the time period of maximum growth of the CBL. During these morning hours we expect to encounter large effects of the entrained air from the nocturnal residual layer and from the free troposphere. Since the entrainment process for other variables like heat and moisture is crucial for the development of the boundary layer, we also discuss what role entrainment plays on the distribution and evolution of these variables. More specifically, the importance of the boundary layer structure on the diurnal variability of the $CO_2$ concentration.

To complete the observational analysis, mixed layer theory is applied to determine the influence of the atmospheric boundary layer growth on the diurnal variability of carbon dioxide (Betts, 1973; Carson, 1973; Tennekes, 1973). By combining both approaches, we are able to estimate the time evolution of the entrainment ratio ($\beta_s$) defined as the ratio of the entrainment flux to the surface flux $\beta_s = -(\overline{ws})_e/(\overline{ws})_o$, where $s$ is a generic scalar variable. The ratio ($\beta_s$) is a crucial closure assumption for the budget analysis, urban modelling studies (Reid and Steyn, 1997) and global modelling studies (Betts and Ball, 1994; Beljaars and Viterbo, 1998).

The $\beta_s$-ratio for virtual potential temperature and specific humidity has been estimated during various experimental campaigns and using different instruments (Betts et al., 1990; Betts, 1992; Grossman, 1992; Betts and Ball, 1994; Davis et al., 1997). To our knowledge, so far there have been no estimates of the order of magnitude and the evolution of the $\beta$-ratio for carbon dioxide.

## 2. OBSERVATIONS

The turbulent measurements presented here are based mainly on the analysis of 23 horizontal flights and 3 spiral vertical profile flights made by the Sky Arrow ERA aircraft above Cabauw (the Netherlands; $51^o\ 58'N, 4^o\ 56'\ E$) on 27 July 2002. In order to obtain reliable statistics and spectra for


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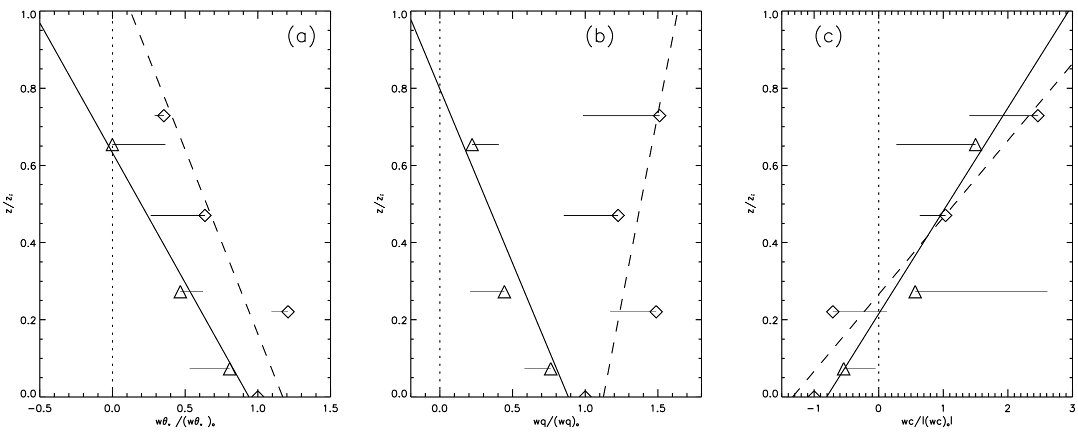


FIG. 1: *Vertical profiles of the fluxes of (a) virtual potential temperature, (b) specific humidity and (c) carbon dioxide. The bars represent the standard deviation from the observations. The fluxes are made nondimensional by their surface value measured at the Cabauw mast. A rhombus represents observations in the morning and a triangle represents afternoon observations. The dashed and continuous lines are linear fits to the observations which includes the values of the fluxes at* $z/z_i = 0$
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the turbulence measurements three or four passages of approximately 8.5 km were flown successively at a constant height. By flying repeatedly over the same flight path, we attempt to reduce and quantify the error that arises because of the random scatter inherent to the turbulent motions in the CBL. We are also able to estimate the error variance in the calculated statistics (Lenschow et al., 1994).

The turbulent fluxes of the virtual potential temperature, the specific humidity and the carbon dioxide with their respective standard deviations are shown in Figure 1. The fluxes observed are scaled by the mixed-layer parameters shown in Table 1. The standard deviation of each flux, calculated from the three or four passages at constant height, reflects the large variability associated in the estimation of the fluxes from aircraft observations by the eddy correlation method. In the figure, the observed mean scalar fluxes at the three different levels have been fitted to a line to show the trend of the flux profile in the whole CBL. Notice that the surface fluxes are included to calculate the fitting lines. By linearly extrapolating the observed fluxes (in the afternoon flights) shown in figure 1 to the top of the CBL, we obtain an indirect estimation of the $\beta-$ratio of the virtual potential temperature, specific humidity and carbon dioxide. The values are respectively: $\beta_{\theta_v}$=0.6, $\beta_q$= -0.25, $\beta_c$=2.9. These values show that during the observed situation the turbulent eddies entrain warmer, dryer and less $CO_2$ containing air from the free troposphere down into the CBL.

## 3. MIXED LAYER MODEL

The mixed boundary layer model is based on the studies performed by (Betts, 1973; Carson, 1973) and (Tennekes, 1973). Briefly, we solve two basic equations for the mixed layer mean value ($< S >$) and for the jump at the inversion ($\Delta S$). The system of the prognostic equations for the generic scalar variable ($s$=$\theta_v$, $q$ or $CO_2$) reads:

$$\frac{\partial < S >}{\partial t} = \frac{[(\overline{ws})_o - (\overline{ws})_e]}{h} \quad (1)$$

$$\frac{\partial \Delta S}{\partial t} = \gamma_s \left(\frac{\partial h}{\partial t} - w_s\right) - \frac{\partial < S >}{\partial t}. \quad (2)$$

Above the jump, the profile of each variable in the free troposphere is characterized by the vertical gradient ($\gamma_s$) and by the mean vertical velocity ($w_s$). This velocity is normally opposite to the boundary layer growth, *i.e* subsidence $w_s < 0$. In applying mixed layer theory to our case, we assume that the horizontal advection contribution is relativately small compared to the flux divergence contribution. We assume that the entrainment flux at the boundary layer height can be described by a zero-order jump model: $(\overline{ws})_e = -w_e \Delta S$ (Betts, 1992). This assumption requires to calculate the entrainment velocity and the difference of the scalar value between the free troposphere ($S_{FT}$) and the boundary layer value $< S >$: $\Delta S = S_{FT} - < S >$.

The entrainment velocity ($w_e$) is related to the boundary layer growth and the mean vertical velocity. In the mixed layer model, we assume that $w_e$ depends on the entrainment flux and the jump

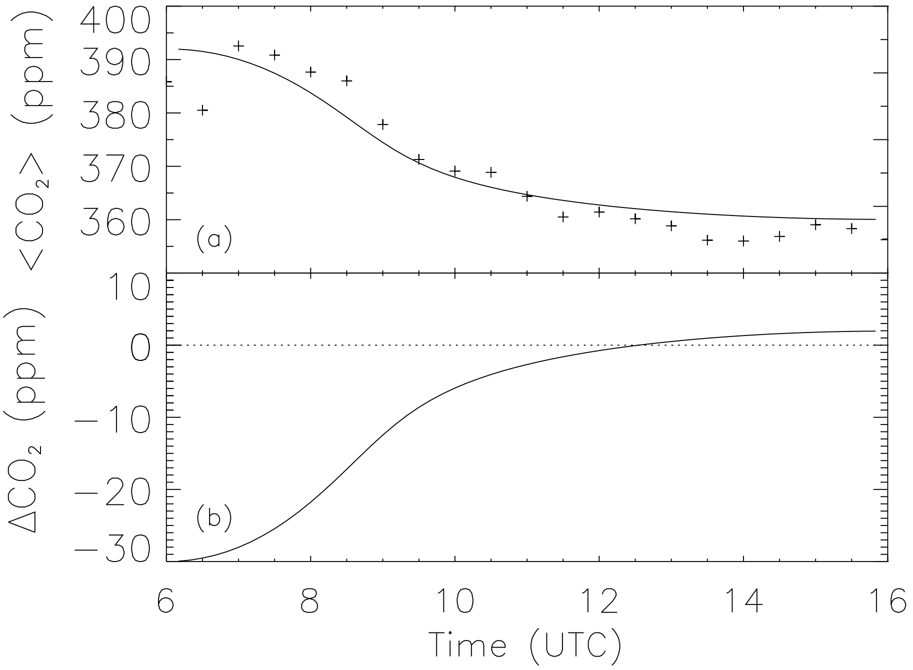


FIG. 2: *(a) Evolution of the carbon dioxide mixing ratio calculated by the mixed layer model (continuous line) and compared with the Cabauw tower observations measured at 200 m. (b) Evolution of the carbon dioxide jump at the inversion calculated with the mixed layer model*

at the inversion of the virtual potential temperature (zero-order model). Thus,

$$w_e = \frac{\partial h}{\partial t} - w_s = -\frac{(\overline{w\theta_v})_e}{\Delta\theta_v} \quad (3)$$

In order to solve (3), we impose the closure assumption that the entrainment flux is a constant fraction ($\beta_{\theta_v}$) of the surface flux, *i.e.* $(\overline{w\theta_v})_e = -\beta_{\theta_v}(\overline{w\theta_v})_o$. In our study, we take the value $\beta_{\theta_v} = 0.4$.

The model is initialized with the 6 UTC observations. The prescribed fluxes for heat, moisture and carbon dioxide follow a diurnal evolution. A very good agreement is found when comparing the mixed layer results with the observations. In particular for the boundary layer depth evolution and for the mixed layer evolution of the virtual potential temperature, the specific humidity and the carbon dioxide mixing ratio. Figure 2a shows that the mixed layer model is able to reproduce the diurnal decrease of the carbon dioxide mixing ratio due to the combined effect of the uptake by the vegetation, the entrainment at the top of the CBL and the growth of the CBL. As figure 2b shows, the entrainment of carbon dioxide is particularly important in the morning hours (until approximately 10 UTC) when the difference in concentration between the boundary layer and the residual layer is large ($\Delta CO_2 < -10\,ppm$).

In figure 3, the time evolution of $\beta_c$ calculated from the mixed layer model is shown. The time evolution of $\beta_c$ shows three distinct periods. The first one (until 10 UTC) is characterized by a dominance of the dilution processes due to the entrainment of free tropospheric air masses with low $CO_2$ concentrations ($\beta_c > 1$). From 10 UTC until 12.30 UTC, the entrainment process is still relevant but the uptake by vegetation ($0 < \beta_c < 1$) progressively becomes dominant. After 12.30 UTC, $\beta_c < 0$, the carbon dioxide is assimilated by the grass at the surface and the $CO_2$-concentration increases because of the mixing with air with relative high concentrations of $CO_2$ originating from the free troposphere. During the studied CBL, the latter process can compensate upto a 10% of the vegetation uptake, *i.e.* $\beta_c = -0.1$.

## 4. CONCLUSIONS

The entrainment process of carbon dioxide in the CBL is studied by combining upper air and surface measurements with mixed layer modelling. The study reveals the importance of the CBL development in determining the diurnal variability of $CO_2$.

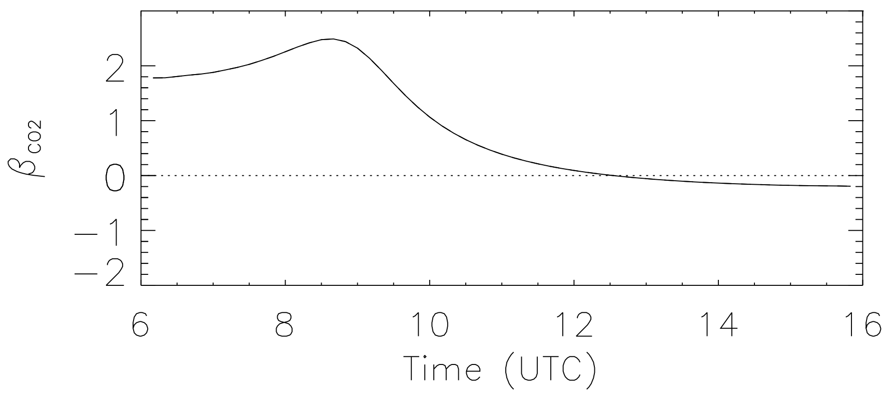


FIG. 3: *Evolution of the ratio of the entrainment flux to the surface flux ($\beta_{CO_2}$) of carbon dioxide calculated by using the mixed layer model.*

In the observed clear convective boundary layer, we estimate the following values of the entrainment flux to the surface flux ($\beta_s = -(\overline{ws})_e/(\overline{ws})_o$); for the virtual potential temperature $\beta_{\theta_v} = 0.6$, for moisture $\beta_q = -0.25$ and for carbon dioxide $\beta_c = 2.9$ . The ratio of the entrainment flux to the surface flux of $CO_2$ points out the relevance of entrainment. A mixed layer model was used to reproduce the observed CBL. Except for the afternoon $CO_2$ flux ratio, the model results are in good agreement with the observations. In particular, the decrease of the $CO_2$ mixing ratio and of the mixing ratio jump at the entrainment zone are very well reproduced. Both variables show a strong dependence on the boundary layer diurnal evolution.

This study therefore suggests that the concentration of $CO_2$ becomes lower in the atmospheric boundary layer during the morning hours due to different processes: the uptake by the grass vegetation at the surface and the dilution by mixing with the low $CO_2$ concentration air masses entrained from the free troposphere. The diurnal evolution of the mixed layer concentration of carbon dioxide therefore strongly depends on the strength of these processes. We find that in the morning the ratio of the entrainment to surface flux ($\beta_c$) is larger than one, which indicates that the entrainment processes are more important than the uptake by vegetation. In the afternoon one can expect values of $\beta_c < 1$ or even $\beta_c < 0$, as shown by previous afternoon aircraft observation reported by (Desjardins et al., 1992). By using a terminology that resembles the one introduced by (Mahrt, 1991), we can define two regimes for the carbon dioxide in the convective boundary layer: an entrainment-diluting regime closely related to the rapidly morning growth of the boundary layer and a surface $CO_2$-assimilation regime which acts as a sink of $CO_2$ throughout the day, but becomes predominant in the afternoon hours. More information and a further analysis of the observations and the mixed layer results can be found at (Vilà and Coauthors, 2004).

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