# P1.2 VERTICAL WIND VELOCITY OBSERVATIONS FROM THE CABAUW TOWER

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## ABSTRACT

If vertical turbulent fluxes are computed from time series collected at a fixed point, it is assumed that the temporal mean vertical velocity is zero. This paper discusses the validity of this assumption by analysis of time series of the vertical wind velocity collected with sonic anemometers at four different heights ranging from 3 to 180 m from the Cabauw tower. It is shown that even for averaging times of 1 hour, the mean vertical velocity can have values of the order of 10 cm/s.

## 1. INTRODUCTION

From the Earth's surface, heat and scalars, like the concentrations of the greenhouse gases carbon dioxide, methane and nitrous oxide, are emitted into the atmosphere. These emissions are determined by measuring the turbulent fluxes of these quantities very close to the surface with the Eddy Covariance (EC) technique. This involves simultaneously measuring both the emitted quantity and the vertical wind velocity at high frequency at a fixed location. To calculate the fluxes of any arbitrary quantity $\phi$ from EC measurements, its signal is decomposed in a time mean, indicated with an overbar ($\overline{\phi}$), and a fluctuating part, indicated with primes ($\phi'$),

$$\phi = \overline{\phi} + \phi'. \tag{1}$$

$$\overline{\phi} = \frac{1}{N}\sum_{i=1}^{N}\phi_i \tag{2}$$

for a time series of $N$ data points. The EC flux for a scalar $\phi$ is defined by the equation

$$\overline{F}_{EC} = \overline{w'\phi'} = \frac{1}{N}\sum_{i=1}^{N}\left(w_i - \overline{w}\right)\left(\phi_i - \overline{\phi}\right), \tag{3}$$

where the vertical velocity has also been split in a temporal mean and a fluctuating part. The total transport through the air is given by the summation of the turbulent flux and the advective flux,

$$\overline{F} = \overline{w\phi} = \overline{F}_{EC} + \overline{F}_{Adv} \tag{4}$$

$$= \overline{w'\phi'} + \overline{w}\,\overline{\phi}. \tag{5}$$

If the sampling time is sufficiently long, it is typically assumed that the mean vertical velocity, $\overline{w}$, is zero and therefore the advective flux is zero as well. However, according to recent Large Eddy Simulations (LES) studies (Kanda et al., 2004; Steinfeld et al., 2007; Huang et al., 2008; Schalkwijk, 2008), the EC technique does not measure the complete flux. According to Mahrt (1998) this occurs if the temporally averaged vertical wind velocity during the measurement period is non-zero. In a numerical study, the model provides for the possibility to examine spatial mean values in the horizontal plane. The slab-averaged value of an arbitrary quantity, $\chi$, is expressed as $\langle\chi\rangle$ and

$$\chi = \langle\chi\rangle + \chi'', \tag{6}$$

where the double prime indicates deviations with respect to the slab mean value. The spatially and time averaged advective flux divided by the spatially and time averaged total flux is called the spatially averaged flux imbalance (Kanda et al., 2004) and is described by

$$\langle I\rangle = \frac{-\left\langle\overline{w}\,\overline{\phi}\right\rangle}{\left\langle\overline{F}\right\rangle}. \tag{7}$$

The LES results show that $\langle I\rangle \neq 0$ for both heat and concentrations, and because in LES models the slab-mean vertical velocity $\langle w\rangle = 0$ at all times, we see from equation (7) that not only the time averaged vertical wind velocity must be non-zero, but also that the time averaged vertical wind velocity is either spatially correlated or anti-correlated to the time averaged scalar. To the knowledge of the authors this effect is as of yet not confirmed by measurements. In this research mean vertical wind velocities are calculated using data from the Cabauw meteorological tower.

## 2. MEASUREMENT SETUP

The measurement data are obtained from the KNMI measurement site at Cabauw, which is located at 0.7 m below sea level at 51°58' N latitude and 4°54' E longitude. Wind velocities are measured at a frequency of 10 Hz by Gill R3 sonic anemometers installed at 60 m, 100 m and 180 m height on beams pointing south east from the Cabaauw tower. An additional sonic anemometer is installed at 3 m height about 200 m north of the main tower. The results presented here are based on the raw 10 Hz measurement data covering the period from 3 May 2008 to 13 May 2008 between 10:00 and 18:32 local time. This period is characterized by clear convective conditions. During this period the wind arrived at the sonic anemometers from a different direction than the

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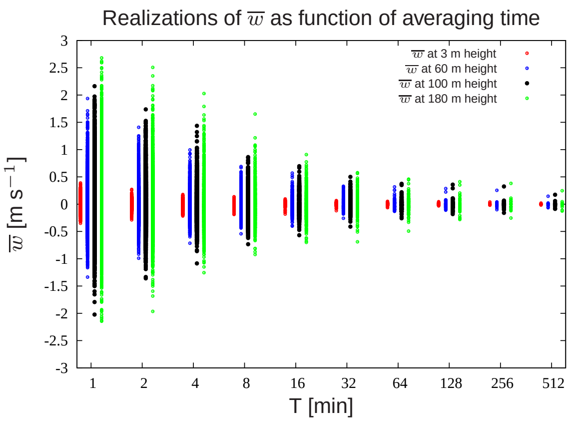


FIG. 1: Temporal averaged vertical wind velocities plotted against the averaging time. This plot is based on data from the Cabauw site, sampled between 10.00 h and 18.32 h local time at four different heights. A wind tilt correction angle is calculated to correct the vertical wind velocities so that they are 0 m s$^{-1}$ on average. After this they are averaged in consecutive blocks of a specific averaging time. For every measurement height this gives a series of time averaged vertical wind velocities, which is plotted. This is repeated for averaging times of 1 minute to 8 hours and 32 minutes.

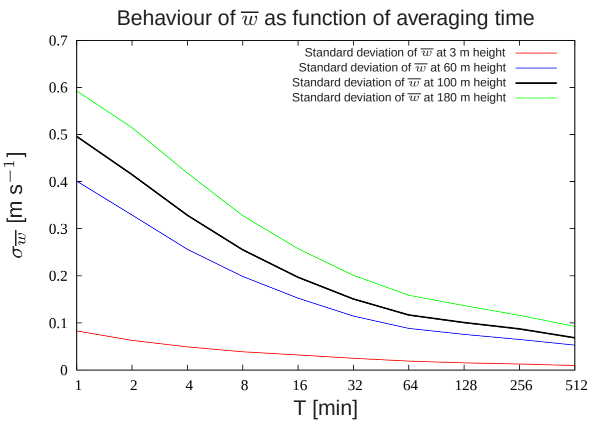


FIG. 2: Standard deviations of the temporal averaged vertical wind velocities plotted against the averaging time. This plot shows per averaging time the standard deviations of the values of $\overline{w}$ plotted in Figure 1.

Cabauw tower, preventing the possibility of flow distortion due to the tower.

It is necessary to correct the measured wind velocities by virtual rotations for bending of the air by the beams and for the sonic anemometer never being placed perfectly aligned perpendicular to the surface. Most methods use the assumption that for the time interval $T$ during which the flux is calculated $\overline{w} = 0$, with $T$ typically in the range between 10 to 60 minutes (Slager, 2001). For the period under investigation the variation of the wind direction was relatively small. Because of this, a single rotation angle was calculated for every sonic anemometer to set the mean vertical wind velocity to 0 m s$^{-1}$ over the full set of daytime data during 11 days. The planar fit and a wind tilt corrections that were applied are explained in detail by Ouwersloot (2009). In addition to observations, experiments were performed using the Dutch Atmospheric Large Eddy Simulation (DALES) model (Heus et al., 2010). In this model, spatial averages of the vertical wind velocity are $0$ m s$^{-1}$.

## 3. RESULTS

The average of the complete corrected data set is $0$ m s$^{-1}$, but that is not necessarily the case for individual measurement periods within that set. The vertical wind velocities are averaged in consecutive blocks of a certain averaging time. For every measurement height this results in a series of temporal averages for that averaging time. This process is repeated for averaging times ranging from 1 minute to 8 hours and 32 minutes. The resulting series of temporal averaged vertical wind velocities are plotted in Figure 1. In order to show a clearer view of the spread in temporal averaged vertical wind velocities, the standard deviations of all four series are calculated per averaging time and plotted in Figure 2. Averaging times in the range between 10 minutes and 60 minutes are typically used. Let us consider the standard deviation of the temporal averaged vertical wind velocities,

$$\sigma_{\overline{w}} = \sqrt{\frac{\sum_{n=1}^{N} \overline{w}_n^2}{N}} \tag{8}$$

with $N$ the number of data blocks. Note that the mean vertical velocity during the full data set is zero. Even for an averaging time of 1 hour, $\sigma_{\overline{w}}$ is still of the order of a tenth m s$^{-1}$, except for the lowest measurement level. This shows that for averaging times $T > 30$ minutes and even for $T > 1$ hour, the mean vertical wind velocities deviate significantly from zero. This leads to the aforementioned flux imbalance. Figure 2 shows that after an hour, longer measurements do not improve the standard deviation of the averages by much. The spread in temporal averaged vertical wind velocities is higher for higher measurement heights and decreases for longer averaging times. At 3 m height, $\sigma_{\overline{w}}$ is much lower. This is likely due to the smaller eddy sizes which have shorter time scales and smaller vertical velocity values due to the presence of the ground surface where $w = 0$. This confirms that the flux imbalance effect at 3 m height is small.

According to general statistics the standard deviation of a variable without correlation on a larger time scale should decrease with the square root of the amount of samples used to determine its value. In this case the standard deviations should therefore decrease with the square root of the averaging time after a certain time if the

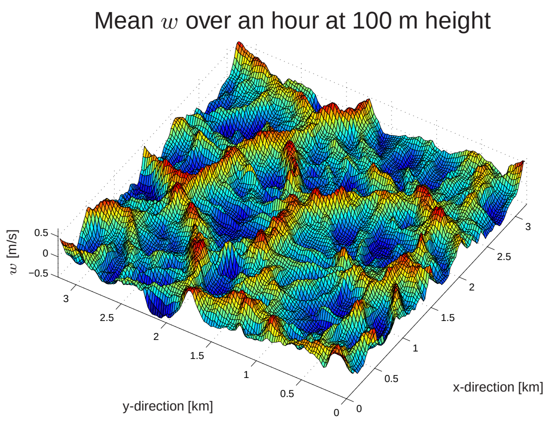


FIG. 3: The vertical wind velocity sampled every minute and then averaged over an hour at a height of 100 m. Data are collected from a DALES simulation of the BOMEX case. The horizontal domain has a size of 3.2 km x 3.2 km and consists of 128 x 128 grid boxes. The resolution is 25 m x 25 m x 40 m. The prescribed surface buoyancy flux is 21 W m$^{-2}$ and the horizontal wind velocity is near 0 m s$^{-1}$. In this figure, the turbulent organized structures are visible.

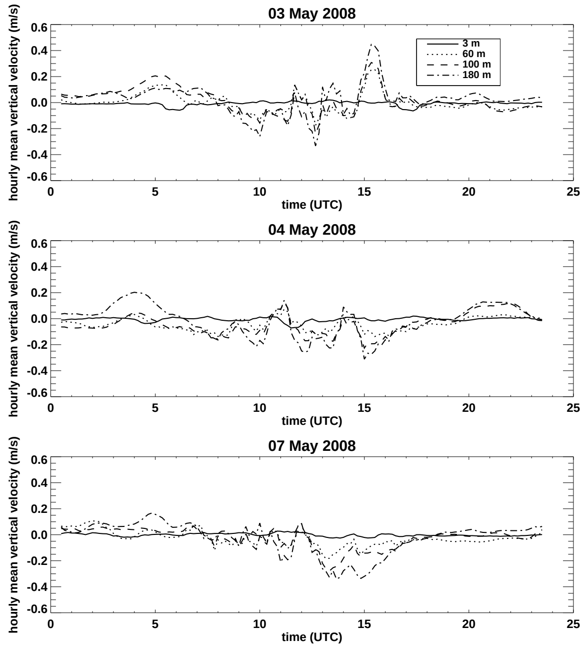


FIG. 4: Hourly averaged vertical wind velocity sampled every 10 minutes. This plot is based on data from the Cabauw site, sampled at four different heights. The same wind tilt correction angles are applied as for the analysis shown in Figures 1 and 2, after which the hourly averages are calculated. The resulting figures for 3 May, 4 May and 7 May are shown. The vertical wind velocity at 3 m height is uncorrelated to the vertical wind velocities at the other heights. The vertical wind velocities at 60 m, 100 m and 180 m height show the same patterns and are highly correlated, supporting the notion of turbulent organized structures.

fluctuations are random for longer time scales. Since the standard deviation always decreases slower than that, a correlation should exist at larger time scales.

This points to turbulent organized structures (TOS), as introduced by Steinfeld et al. (2007). These are persistent structures in the temporal mean vertical velocity fields, even for averaging times of 1 hour. As an example the temporal mean vertical velocity as obtained from DALES is shown in Figure 3. Analysis of the LES fields show similar results as shown in Figures 1 and 2.

To further visualize the presence of the TOS, the aforementioned observational data from the Cabauw measurement site is used. For this analysis all data are used instead of a selected time period, but the same virtual rotation angle is applied for every height as previously determined. Every 10 minutes, hourly averaged vertical wind velocities are computed. In Figure 4 the resulting data are shown for all 4 measurement heights for 3 May, 4 May and 7 May 2008. This shows that the vertical wind velocity at 3 m height is uncorrelated to the vertical wind velocities at 60 m, 100 m and 180 m height. However, the vertical wind velocities at those 3 heights are highly correlated with each other and show a very similar pattern. Since observations are performed by separate sonic anemometers, and because the virtual rotation angles are calculated independently at each height, Figure 4 indicates that a dynamical correlation between vertical wind velocities at different heights is present. This validates the notion of turbulent organized structures.

Another indication that the vertical wind velocity are not diluted by poorly executed virtual rotations, is shown in Figure 5. It shows the hourly averaged horizontal wind velocity ($U = \sqrt{\overline{u}^2 + \overline{v}^2}$) for the same heights and days as Figure 4. If dilution would be present, a correlation between $w$ in figure 4 and $U$ in figure 5 would be visible. This is not the case.

## 4. CONCLUSIONS

This paper discusses the assumption that $\overline{w} = 0$ m s$^{-1}$. From observational data it is shown that the temporal mean vertical wind velocity deviates significantly from 0 m s$^{-1}$, even over a long time, thereby confirming previous modelling studies. The behaviour of the temporal averaged vertical wind velocities is similar for observational and simulated data, indicating that the turbulent organized structures witnessed in large eddy simulation studies are present in real life as well.
Because the temporal mean vertical wind velocities are non-zero, flux imbalance effects become important at higher measurement levels. It also poses a problem to interpret data of sonic anemometers. Observational data have to be virtually rotated in order to compensate for non-perfect aligning, but the time period over which $\overline{w}$ can

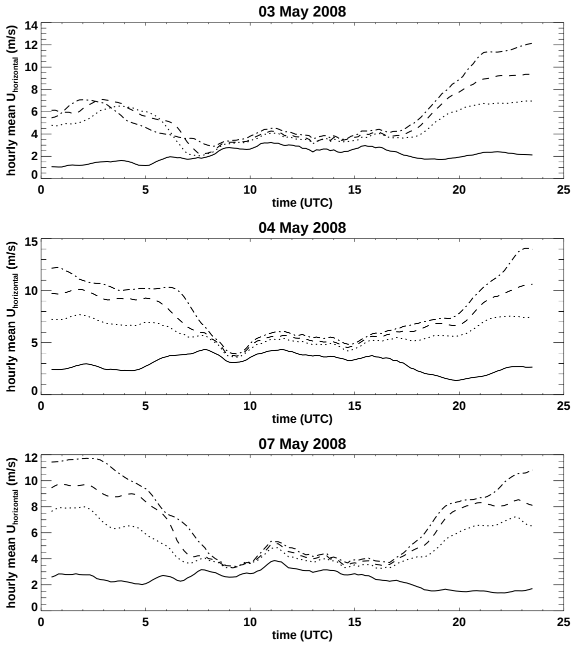


FIG. 5: Hourly averaged horizontal wind velocity, sampled every 10 minutes. This plot is based on the same data as used for Figure 4. The evolution of the horizontal wind velocities is uncorrelated to the evolution of the vertical wind velocities.

be considered to be 0 $\text{m s}^{-1}$ is open to discussion. More on this topic is treated by Ouwersloot (2009).

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