Chapter 5
Nighttime Flux Correction

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5.1 Introduction

5.1.1 History

Since the early tests performed with eddy covariance systems (Ohtaki 1984; Anderson et al. 1984), and the paper of Goulden et al. (1996), it became clear that the eddy covariance method underestimates the CO_2 flux in stable conditions. This underestimation acts as a selective systematic error (Moncrieff et al. 1996) and could lead to a strong overestimation of net ecosystem exchange (NEE) at an annual scale.

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The problem has now been confirmed by many researchers working on very different sites: In tropical (Grace et al. 1996; Loescher et al. 2006; Hutyra et al. 2008), boreal (Jarvis et al. 1997; Pattey et al. 1997), temperate mixed (Aubinet et al. 2001; Teklemariam et al. 2009), broadleaved (Pilegaard et al. 2001; Cook et al. 2004), or coniferous (Berbigier et al. 2001; Carrara et al. 2003; Turnipseed et al. 2003) forests as grasslands (Wohlfahrt et al. 2005) or crops (Moureaux et al. 2006). First intersite evaluations of this error were proposed by Aubinet et al. (2000) (ten forested sites) and Gu et al. (2005) (five forest and two grassland sites). They confirmed that practically all the sites were affected significantly by a night flux error which necessitates an adequate correction.

5.1.2 Signs Substantiating the Night Flux Error

Like all systematic errors, the night flux error is not easy to distinguish as its detection would require a comparison of eddy fluxes with independent evaluations of ecosystem respiration at the same spatial and temporal scale. As such measurements are not available, the sole possibility is to refer to indirect proofs. Goulden et al. (1996) put two symptoms forward: First, total ecosystem respiration estimates are generally lower when estimated by eddy covariance than when obtained by a bottom up approach. Second, at night, the turbulent flux is sensitive to the friction velocity (u_*) while there is no evident reason for the biotic flux being sensitive to this variable. These two indices are discussed in the paragraphs below.

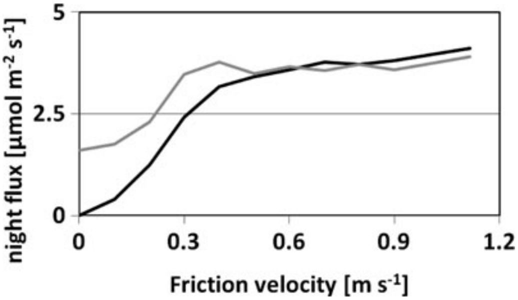
5.1.2.1 Comparison with Bottom Up Approaches

A comparison of eddy flux measurements with alternative flux estimates is always delicate as it is not possible to find measurements that are performed at the same spatial and temporal scale. Generally, such estimates are extrapolated from soil and plant respiration measurements obtained with soil chamber and branch bags. These estimates are themselves subject to instrumental errors and to a large uncertainty due to spatial variability. In addition, the comparison requires both spatial and temporal extrapolation as chamber measurements are performed at smaller scale and, most often, at weekly or monthly scale. Several studies based on this approach (Goulden et al. 1996; Lavigne et al. 1997; Lindroth et al. 1998; Kutsch et al. 2008; Hutyra et al. 2008) confirmed the underestimation of night fluxes by the eddy covariance approach. In addition, these studies provide a procedure to evaluate the importance of this error and to correct it.

5.1.2.2 Sensitivity of Flux to Friction Velocity

The second symptom supporting the existence of a night flux error is the sensitivity of eddy flux to friction velocity in stable conditions (Fig. 5.1). Indeed, as the mechanisms controlling night fluxes are linked to plant and soil respiration, they

Fig. 5.1 Typical evolution of night flux with friction velocity. Average on three successive vegetation periods (May to September) at the Vielsalm site. *Black curve*: eddy flux only, *Gray curve*: eddy flux and storage change



are expected to be independent of u_*. Therefore, any dependence on u_* should come from an artifact. This assertion calls, however, for some comments: First, it could be true only if friction velocity does not covary with respiration driving variables, as temperature and soil humidity. In order to avoid any confounding effect of these variables with friction velocity it is thus recommended to normalize respiration by these variables before to establish the relation with u_* (Aubinet et al. 2000).

Second, the independence of soil respiration to friction velocity is questioned by several authors who mentioned the possibility of a pressure-pumping mechanism. Gu et al. (2005) suggested that, as the CO_2 mixing ratio difference between air and the first soil layers is large, air movement into and out of the soil induced by pressure fluctuations may introduce a significant physical component to the soil efflux that adds to the biological component. Such component could be related to turbulence inducing a relation between night flux and friction velocity. However, this component is mainly significant at sites where the soil exhibits a large porosity (Takle et al. 2004), especially above snow (Massman et al. 1997; Massman and Lee 2002) or on volcanic soils (Rogie et al. 2001). In addition, as such fluctuations could explain an increase of night flux at large u_*, it could not explain the turbulent flux decrease that is observed in very low turbulent conditions.

5.1.3 The Causes of the Problem

Massman and Lee (2002) listed and discussed in detail the possible instrumental errors affecting turbulent flux measurements (see also Chaps. 4 and 7). However, as instrument problems contribute to the flux loss, they suggested that it was mainly meteorological in nature. Meteorological problems are generally identified as follows:

1. Sublayers develop between the measurement system and the surface so that the system is decoupled from the surface and the eddy flux and change in storage terms are no longer representative of the local flux.
2. Even in the absence of a sublayer, the flux may be not representative of the surface because the extent of the flux footprint.

3. In low turbulence, the advection terms gain importance and are no longer negligible (Lee 1998; Aubinet et al. 2003, 2005; Feigenwinter et al. 2004; Marcolla et al. 2005).
4. Strong concentration or velocity changes could appear so that conditions become nonstationary, which invalidates the hypotheses underlying the eddy covariance method.
5. Similarity conditions are not always fulfilled in the stable boundary layer (Mahrt 1999), which makes quality tests, corrections, and footprint evaluation to some extent impossible.

From these different problems, the third appears as the most important that explains a systematic underestimation of the flux. To better understand this problem we will refer to the CO_2 mass conservation (Eq. 1.25).

$$\underbrace{\int_0^{h_m} \overline{\rho}_d \overline{\frac{\partial \chi_s}{\partial t}} dz}_{I} + \underbrace{\int_0^{h_m} \left[\overline{\rho_d w} \frac{\overline{\partial \chi_s}}{\partial z} \right] dz}_{IIa} + \underbrace{\int_0^{h_m} \left[\overline{\rho_d u} \frac{\Delta \overline{\chi}_{s,x}}{\Delta x} + \overline{\rho_d v} \frac{\Delta \overline{\chi}_{s,y}}{\Delta y} \right] dz}_{IIb} + \underbrace{\overline{\rho_d w' \chi'_s}|_{h_m}}_{IV} = \underbrace{F_s}_{V} \tag{1.25}$$

In the generalized eddy covariance method, it is assumed that the stationarity and homogeneity criteria are met so that advection terms (II) can be considered as negligible compared with the change of storage (I) and eddy covariance (IV) terms. These conditions are probably not met in night conditions, which leads either to an incorrect evaluation of terms I and IV, or to increased terms II that can no more be neglected compared to the two former.

5.2 Is This Problem Really Important?

Box 5.1

- The night CO_2 flux error appears at all sites during low turbulent nights. In most cases, it leads to an underestimation of the scalar source/sink intensity.
- When a complete data set is not necessary (which is the case when establishing functional relationships, for instance), it is recommended to discard data collected during low turbulence using a filtering procedure.
- When these data are necessary (for long-term budgets), they should be corrected.
- Storage is most often not enough to correct the fluxes but it has to be considered when a filtering/parameterization procedure is applied.

5.2.1 *In Which Case Should the Night Flux Error Be Corrected?*

There is now experimental evidence that night flux underestimation affects practically all the sites (Schimel et al. 2008). As the night flux error acts as a systematic error, it seems clear that a data treatment is necessary in order to offset it.

This treatment cannot be simply the addition of storage to the turbulent flux, as will be shown in Sect. 5.2.2. It could be different according to the data purpose: if the aim of the data analysis is to infer functional relationships, a data filtering could be sufficient. On the other hand, if long-term flux budgets are required, all data affected by the error should be corrected.

The way filtering procedures should be implemented is presented in Sect. 5.3, while correction procedures are described and evaluated in Sect. 5.4. In the following parts of this section, we will discuss the role of the storage (Sect. 5.2.2), present some assessments of the night flux error on cumulated sequestration (Sect. 5.2.3) and on functional relationships (Sect. 5.2.4), and, finally, evaluate its impact on other tracer fluxes (Sect. 5.2.5).

5.2.2 *What Is the Role of Storage in This Error?*

This section tries to answer two questions: (1) Can the night flux error be corrected by only adding the storage term to the turbulent flux? (2) How to introduce the storage in filtering and correction procedures?

From Sect. 5.1, it arises that the main cause of the night flux error is that storage flux and advection become important compared to the turbulent flux in low turbulent conditions. However, the problem is not the same if the term that competes with the turbulent flux is the storage or the advection (Fig. 5.2).

In the first case, it means that the CO_2 that is respired by the ecosystem accumulates in the air below the measurement system and would be released as soon as turbulence would onset (Fig. 5.2b). In these conditions, the flux capture by the measurement system would simply be delayed. This would be without impact on long-term budget but would however induce a bias on half hourly flux estimates and, consequently on the relationships between these fluxes and climate variables. Grace et al. (1996), Berbigier et al. (2001), and Dolman et al. (2002) considered in particular that the night flux underestimation at their site resulted only from storage and, consequently, did not apply any further night-data filtering to their data when computing annual sums. However, we think that these cases remain the exception rather than the rule.

In the second case, the respired CO_2 is removed from the ecosystem by advection and is definitively lost by the measurement system (Fig. 5.2c). In this case, a treatment is necessary not only for half hourly estimates but also for long-term budgets.

In most cases, both these processes take place simultaneously (Fig. 5.2d). As a consequence, a data filtering or correction is necessary, but there is a risk that it

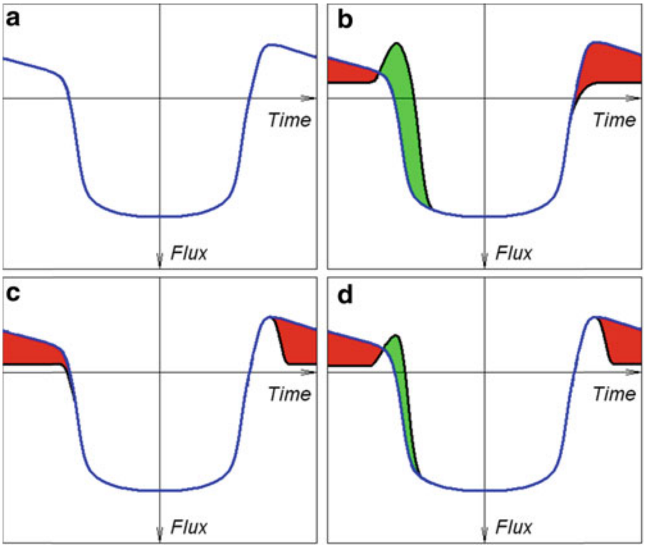


Fig. 5.2 Idealized dial evolution of CO_2 flux exchanged by an ecosystem. (**a**) (and *blue curve* in all other figures): Expected evolution of the biotic flux (the flux decrease at night mimics a response to temperature), (**b**) (*black curve*): Expected measured flux if the night flux underestimation is only due to storage change (the *red* and *green* surfaces compensate), (**c**) (*black curve*): Expected measured flux if the night flux underestimation is only due to a nonturbulent evacuation of CO_2 respired at night. See Sect. 5.4.1 for the peak explanation in early evening, (**d**) (*black curve*): Expected measured flux when both storage change and nonturbulent transport are responsible for the night flux underestimation (the *red* and *green* surfaces do not compensate)

leads to an overstated correction. This point should be considered with care when applying the filtering or the correction procedures, and will be discussed in detail in Sects. 5.3 and 5.4.

5.2.3 *What Is the Impact of Night Flux Error on Long-Term Carbon Sequestration Estimates?*

The night flux error acts as a selective systematic error (Moncrieff et al. 1996), that is, it affects much more night flux measurements, when the ecosystem behaves as a source, than day flux measurements, when the ecosystem behaves as a sink. As a result, it always leads to a carbon sequestration overestimation. The importance of the error varies from site to site and depends at the same time on local average meteorological conditions (frequency of occurrence of nonturbulent periods), on site topography, on land cover heterogeneity, on soil and plant biology (importance of respiration), and on canopy architecture (vegetation height, canopy density).

An assessment of this error could be obtained by comparing u_* corrected and noncorrected NEE estimates. Such estimates have been extensively presented in the literature. These results are gathered in Table 5.1. Tropical forests appear to be the most sensitive to the error that could reach 200 to more than 400 g C m^{-2} $year^{-1}$. This is because these forests are high, dense, and generally subjected to intense respiration fluxes. It could reach more than 100 g C m^{-2} $year^{-1}$ in Mediterranean forests, 50–90 g C m^{-2} $year^{-1}$ in temperate forests, and generally lesser than 50 g C m^{-2} $year^{-1}$ in crops and grasslands.

5.2.4 What Is the Impact of the Night Flux Error on Functional Relationships?

Night flux underestimation may also affect flux–climate relationships. Most usual flux relationships relative to CO_2 fluxes are the photosynthetically active photon flux density (PPFD) response of day flux and the temperature response of night flux. Night flux error induces both random and systematic error in the night flux response to temperature as it increases data spread and leads to an underestimation of the relationship parameters, that is, respiration at 10°C and temperature sensitivity. The response to PPFD of day flux may also be affected as the left end of the curve corresponds to low PPFD, generally associated to the beginning or the end of the night. Contrasting results may be observed: at sunrise, stable conditions often reduce turbulence while soil cooling is not large enough to generate advection. In these conditions, the CO_2 accumulation is especially important and turbulent fluxes underestimate the source/sink term. At sunset, following turbulence onset, the CO_2 accumulated at night is evacuated which may lead, on the contrary, to turbulent fluxes that overestimate the source/sink term. Conjunction of sunrise and sunset data in the flux to PPFD relationships may thus lead to both over- and underestimation of the flux. This generates an important data spread and, consequently, large uncertainties on the intercept (dark respiration) and the initial slope (quantum yield) of the light response. One could think that the problem could be solved by adding storage change to the turbulent flux. Unfortunately, half hourly storage estimates are themselves subject to a large spread so that this rarely improves the problem.

5.2.5 What Is the Impact of the Night Flux Error on Other Fluxes?

As the night flux problem results mainly from atmospheric processes that hinder the turbulent transport of tracers, it should affect any passive tracer that, similarly than for CO_2, could be exchanged by the surfaces at night and whose flux would be mainly controlled by production/absorption mechanisms that carry out independent of the presence or absence of turbulent transport.

Table 5.1 Impact of night flux correction on annual carbon sequestration at different sites

Site	Author	noncorrected	corrected	Δ	Threshold	% missing
Forest temperate conifer 15						
Tharandt 2001	Papale et al. (2006)	−623	−574	49	0.19	
Tharandt 2002	Papale et al. (2006)	−674	−623	51	0.18	
Hainich 2001	Papale et al. (2006)	−591	−559	32	0.35	
Hainich 2002	Papale et al. (2006)	−593	−530	63	0.35	
Braschaat 1997–2001	Carrara et al. (2003)	−171	−110	61	0.2	56
Loobos 1997	Dolman et al. (2002)	−338	−338	0	/	0
Kiryu 2003–2004	Ohkubo et al. (2007)	−798	−589	209	0.5	
Yamashiro 2000–2002 (mixed)	Kominami et al. (2008)	−312	−127		0.4	80
Forest boreal 2						
Hyytiala 2001	Papale et al. (2006)	−221	−178	43	0.2	
Hyytiala 2002	Papale et al. (2006)	−299	−215	84	0.25	
Forest temperate deciduous 9						
Vielsalm 2001	Papale et al. (2006)	−600	−538	62	0.3	
Vielsalm 2002	Heinesch et al. (2007)	−680	−545	75	0.5	62
Hesse 2001	Papale et al. (2006)	−575	−592	−18	0.1	
Hesse 2002	Papale et al. (2006)	−582	−608	−26	0.1	
Soroe 1996–1997	Pilegaard et al. (2001)	−240	−183	57	0.25	
Takayama 1999–2001	Saigusa et al. (2005)	−323	−266	57	0.2	
Forest mediterranean 3						
Puechabon	Papale et al. (2006)	−445	−302	143	0.18	
Yatir	Papale et al. (2006)	−240	−174	66	0.21	
Roccarespampani	Papale et al. (2006)	−151	−12	139	0.13	

(continued)

Table 5.1 (continued)

Site	Author	non corrected	corrected	Δ	Threshold	% missing
Forest tropical 6						
Santarem (Brasil)	Saleska et al. (2003)	−390	+40	430		
Tapajos Nat. For.	Hutyra et al. (2008)	−340	+95	435	0.22	
Pasoh (Malaysia)	Kosugi et al. (2008)	−850	−580	270	0.2	
Grasslands 2						
Schidler	Falge et al. (2001)	−431	−355, −383[a]	48, 76		
Sierra Nevada	Xu and Baldocchi (2004)	−90	−51	39		
Crops 6						
Lonzée SB 2004	Moureaux et al. (2006)	−620	−590	30	0.2	27
Lonzée, WW 2005	Moureaux et al. (2008)	−670	−620	50	0.3	
Gebesee, WW	Anthoni et al. (2004)	−320	−215	105	0.3	
Bondville, Corn	Falge et al. (2001)	−547	−526, −563[a]	−16, +21		
Bondville, Soybean	Falge et al. (2001)	129	125, 165[a]	−36, +4		
Ponca City, WW 1997	Falge et al. (2001)	−249	−147, −174[a]	75, 102		

Nc noncorrected sums, *c* sum corrected using u^* filtering, Δ difference, *Threshold* u^* threshold selected for u^* filtering, *% missing* percentage of data removed by the filtering

[a] Two different values are given, depending on the data gap filling method

First, tracers whose fluxes are negligible at night, such as water vapor and isoprene, could be considered as not concerned by such problem. For other tracers, like sensible heat, methane, monoterpenes, methanol, nitrous oxide, ozone, or NOx the situation is more complex. In these cases, a careful and specific analysis is needed for each tracer to determine if the flux decrease under low turbulence (if any) is the result of a measurement artifact or of a real flux slowing down. When the flux is not controlled by production/absorption processes at the surface but rather result from a diffusive exchange between a reservoir and the atmosphere, as is the case in deposition processes for example, the dependence of the flux on turbulence could be real. In these conditions, the night flux correction is not recommended for long-term budgets as it could lead to a large flux overestimation.

In addition, night flux effect could be very different if the gas is passive or reactive. In the first case, a behavior similar to those of CO_2 would be expected while the second situation would be more complex. Indeed, the turbulence limitation, by hindering atmospheric transport, would limit not only the tracer flux but also the reactive transport and, by this, the reactive encounters and their mutual destruction. In these conditions, the residence time of reactive components could therefore be prolonged under low turbulence.

The effect of chemical destruction of an emitted compound on its above canopy flux depends on the chemical lifetime of the compound, and the effectiveness of turbulent transport. The ratio of the turbulent mixing time scale to the chemical life time, called Damköhler number (Damköhler 1940), can be used to assess the importance of chemistry on fluxes. The Damköhler number can be written as

$$Da = \frac{\tau_*}{\tau_c}, \tag{5.1}$$

where mixing time scale can be estimated as $\tau_* = (h_m - d)/u_*$. The chemical lifetime, τ_c is the time constant characterizing the degradation of the compound characterized by its mixing ratio χ_R. The differential equation describing this degradation may write:

$$\frac{d\chi_R}{dt} = -\sum_{i=1}^{N} k_i \chi_i \chi_R - k_{photolysis} \chi_R \tag{5.2}$$

From which τ_c can be deduced:

$$\tau_c = \left(\sum_{i=1}^{N} k_i \chi_i + k_{photolysis} \right)^{-1} \tag{5.3}$$

where χ_i refers to different oxidant concentrations, k_i is the rate constant for the reaction between the oxidant and the compound, and $k_{photolysis}$ is the photolysis rate.

Using stochastic Lagrangian transport model, Rinne et al. (2007b) estimated that the above canopy flux is significantly reduced already at Damköhler number values well below 0.1. As the friction velocity is typically lower during night, the mixing time scale tends to be longer. Also the chemical lifetime of a compound can be different during day and night. For example, hydrocarbon compounds (e.g. isoprene and monoterpenes) react in the surface layer with ozone, hydroxyl radical, and nitrate radical, all of which have their different diurnal cycles. Thus one needs to calculate the chemical lifetime for different conditions (day, night) to assess the possible importance of the chemistry on fluxes.

Dependence of sensible heat on u_* has been supported indirectly by analyzing energy balance closure in night conditions. Indeed, at night, the numerator of the closure fraction (CF), defined as: $CF = \frac{H+\lambda E}{Rn+G}$, depends only on turbulent fluxes (i.e., mainly on sensible heat as latent heat is negligible at night), so that the evolution of CF with the friction velocity is an indication of the sensible heat underestimation at night.

Decreases of the CF at low friction velocities were pointed out in particular by Aubinet et al. (2000), Turnipseed et al. (2002), Wilson et al. (2002), Barr et al. (2006), and Tanaka et al. (2008). In addition, Barr et al. (2006) highlighted the similarity between CF and normalized NEE evolutions with u_* at night, showing in particular that the u_* threshold were similar for the two tracers.

Evidence for a night flux dependence on u_* were found notably for ozone (Fig. 5.3a) by Rannik et al. (2009) and for monoterpenes (Fig. 5.3b) by Laffineur (comm. Pers.). However, in none of these cases there is an evidence for mechanism that should produce or absorb these gases independently of turbulence. It is thus possible that these responses reflect a real flux dependency on turbulence.

Many authors systematically sort their data by the mean of a u_* filter before analyzing them. This is especially the case of Rinne et al. (2007a) for methane or Davison et al. (2009) for methanol, acetaldehyde, acetone, and monoterpenes. Here again, a careful analysis of the mechanisms underlying the exchange is necessary in order to determine if the flux dependency on turbulence is the result of a measurement artifact or of a real production/absorption slowing down. The application of a night flux correction for long-term budgets would be relevant only in the first case.

5.3 How to Implement the Filtering Procedure?

5.3.1 General Principle

Filtering methods consist in discarding eddy flux measurements taken during conditions where the eddy covariance measurement is considered as nonrepresentative of the biotic flux. When necessary (for computing sums, e.g.) the gaps created

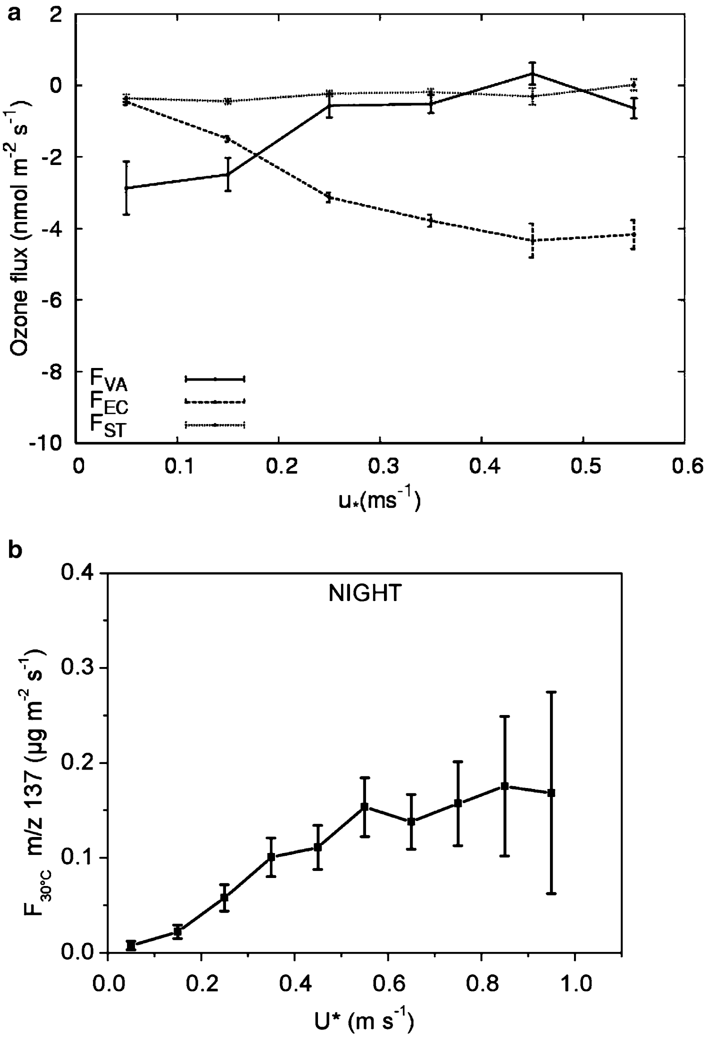


Fig. 5.3 $u*$ response of other tracer fluxes (**a**) Ozone fluxes at Hyytialla. F_{EC} eddy covariance measurements, F_{ST} storage change, F_{VA} advection (Courtesy of Rannik et al. 2009), (**b**) Monoterpene fluxes at Vielsalm (Laffineur, comm. pers.)

by the filtering could be filled. These aspects are discussed in Sect. 5.4. Here we concentrate on the filtering itself, the main questions relevant to this procedure being the determination of the most adapted criterion to discard periods affected by the night flux error and the implementation of the filtering procedure.

5.3.2 Choice of the Selection Criterion

Considering that the night flux problem arises essentially when turbulence is insufficient, Goulden et al. (1996) proposed to use a criterion based on the friction velocity, that is, data measured when u_* is below a given threshold, $u_{*\mathrm{crit}}$, being discarded.

This threshold is identified by looking at flux vs u_* relations: As the biotic flux is expected to not depend on friction velocity, $u_{*\mathrm{crit}}$ could be identified as the threshold below which the flux decreases with decreasing u_*. Alternative criteria have been proposed. However, if some of them could appear relevant, we will concentrate in the following sections on u_* filtering, as this is the procedure mostly used at present. We will show in Sect. 5.3.3 how the method may be implemented and discuss some difficulties that could appear during this implementation. Finally, in Sect. 5.3.4, we will discuss the pros and cons of the approach and introduce some of these alternative filtering criteria.

5.3.3 Filtering Implementation

The most critical question is to choose correctly the friction velocity threshold $u_{*\mathrm{crit}}$, that is, to determine the u_* range in which eddy fluxes can be considered as reliable. This range depends on local topography, surface roughness and heterogeneity, source distribution and intensity, so it varies from site to site and, at a given site, may vary from season to season. The use at a given site of a "standard" threshold derived from literature may indeed lead either to an excessive selection of the data (if too large) or, worse, to a bias in the correction (if too small). It is therefore recommended to make a specific evaluation of the threshold at each site.

Gu et al. (2005) suggested that the data selection should be operated not only below a lower threshold but also above a higher threshold, in order to take account of turbulent flux contamination by pressure pumping under high turbulence. The relevance of such an upper threshold is still a matter of discussion and is not confirmed at all sites.

The lower threshold is site specific and, even, could vary at one given site according to the period. It is especially the case on crops (Moureaux et al. 2008; Béziat et al. 2009). It needs thus to be evaluated individually. This evaluation results from a compromise: on the one hand, the threshold should be as small as possible in order to minimize the number of data that are discarded and, therefore, the random uncertainty on night flux data; on the other hand it should be large enough in order not to introduce any systematic bias on the cumulated NEE value. One can define the lower threshold as the lowest value above which NEE becomes insensitive to the threshold changes. This threshold can be identified by sorting nighttime NEE data by u_* classes and performing statistical comparison between each class-averaged NEE. The threshold is then defined by the lowest u_* value for which the difference

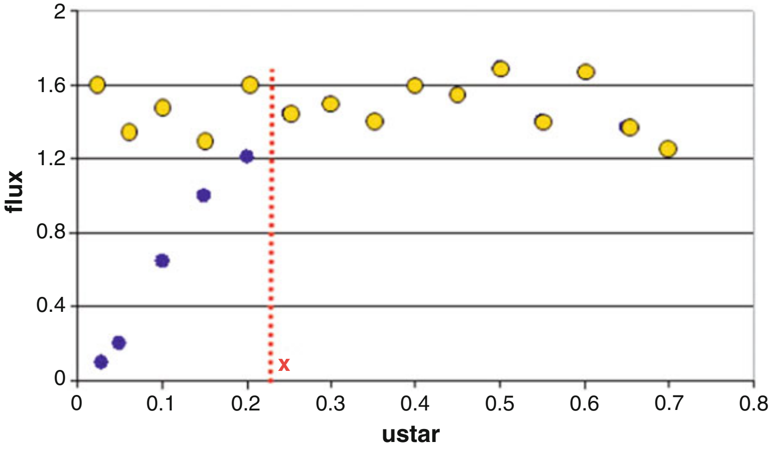


Fig. 5.4 u^* threshold selection (theoretical and optimal situation): *blue dots* are normalized nighttime fluxes (or nighttime fluxes acquired in a narrow temperature range) storage corrected, *yellow dots* are the theoretical pattern of the fluxes (independent by u^*), *red x* is the u^* threshold

between the corresponding averaged NEE is not significantly different from the plateau-averaged NEE (Fig. 5.4). Gu et al. (2005) and Reichstein et al. (2005) proposed algorithms implementing this procedure. In practice, the lowest threshold varies typically from 0.1 to 0.5 m s^{-1} according to the sites.

The preceding approach is valid only if there is a guarantee that friction velocity does not covary with other climatic respiration-driving variables. Indeed, if such covariation exists, it could induce some night flux response to u_* that would not design necessarily a night flux error. In order to avoid such covariation, it is recommended, before sorting NEE according to u_* classes, to plot u_* against the main driving variables and, if any relation is detected, to first perform a normalization by using functions describing NEE response to these driving factors. In temperate regions, normalization by a temperature function is generally used (Aubinet et al. 2000) (Fig. 5.4).

The filtering approach may lead to a flux overestimation in presence of storage. If a part of the flux underestimation during calm periods resulted from CO_2 accumulation below the measurement point, this flux would be restored as soon as turbulence onsets. In these conditions, the u_* filtering, by removing the calm period where the flux is underestimated and keeping the turbulence onset period where it is overestimated, would lead to a global respiration overestimation. If, in addition, the calm period data were replaced by any parameterization (filtering – data gap-filling approach, see Sect. 5.4.2), the part of emitted flux that would have been stored for a short while would have been counted twice. To avoid such bias, NEE estimate must take storage change into account. The introduction of storage leads thus generally to a reduction of the correction brought by u_* filtering (Fig. 5.2d; Box 5.2).

Box 5.2: Steps Recommended in Order to Apply the u* Filtering Procedure

1. Compute the storage change. It is given by $\int_o^{h_m} \rho d \overline{\frac{\partial \chi_c}{\partial t}} dz$. This term is computed by approximating the spatial integral by a weighted sum of different concentrations measured along a vertical profile. In forest sites, the vertical profiles should include as many sampling points as possible (at least four), distributed following a logarithmic pattern along the vertical. In grasslands and croplands, where the measuring height is lower, the profile could be approximated by a single point. The time derivative is approximated by a finite difference between instantaneous concentrations during consecutive half hours.
2. Compute night flux data as the sum of turbulent flux and storage change.
3. Sort night flux data by increasing u_*.
4. Evaluate if there is covariation between u_* and other respiration-driving variables (most often the temperature). If yes, normalize the data in order to get rid of covariation of respiration with this variable.
5. Set a number of u_* classes (normally between 20 and 30) and calculate the mean NEE for each class.
6. Determine the threshold by comparison between NEE in each u_* class and the average of the mean NEE values measured at higher u_*. The new threshold is reached when the NEE of a given u_* class become significantly different from the mean NEE at higher u_*.
7. Remove data situated below the under threshold.
8. If an upper threshold is relevant, same scheme should be followed.

5.3.4 Evaluation

An absolute evaluation of the approach is, however, difficult in the absence of independent flux measurement methods as it aims at correcting a selective systematic error which is unknown. As a result, uncertainties may remain after u* filtering that are due to an incomplete (or an overstated) correction.

The first criticism is that the way the selection is operated is empirical. First, the choice of the criterion is questionable, second there is no guarantee that the data filtering removes all bad data and neither that it removes only bad data.

Acevedo et al. (2009) recalled that u_* represents a flux and could also be contaminated by mesoscale movements. They proposed to use the standard deviation of vertical velocity component, σ_{w}, as an alternative criterion to u_* as this latter variable did not suffer from this flaw. By applying filtering procedures based either on σ_{w} or on u_* on three Amazonian sites, they showed that the first procedure represented a significant improvement, with two main consequences: easier determination of the threshold and larger respiration rates of the series classified as turbulent.

Another flaw of the approach is that u_* is generally evaluated from turbulence measurements made at the canopy top. However, in the case of tall vegetation, decoupling may appear between the wind field above and below the canopy so that the value of u_* above the canopy may be not representative of the turbulence and wind field in the canopy.

Some experiences highlight events during which the u_* filtering failed in keeping wrong measurements: abnormally high turbulent fluxes have been observed at two forest sites (Cook et al. 2004; Rebmann et al. 2010) under well-mixed periods (not removed by the u_* filter). These fluxes were supposed to result from CO_2 advection from pools where it had accumulated.

Wohlfahrt et al. (2005), measuring in an alpine pasture, showed that the direct application of the u_* criterion led to an overestimation of the selected flux data, compared to chamber estimates. By adding a stationarity screening to the u_* filtering, he got more defensible flux estimates. A hypothesis could be that the site is subjected to intermittent turbulence so that turbulent events correspond to releases of CO_2 accumulated during the preceding calm periods.

Finally, the method remains questionable in the cases of sites where no discernable plateau can be observed in the flux/u_* relationship.

Despite these flaws, the u_* filtering has been successfully used in many cases: in particular, u_*-filtered data have often been used to find ecologically relevant functional relationships (see, in particular: Janssens et al. 2001; Suyker et al. 2005; Moureaux et al. 2006; Zhao et al. 2006). This method also has the advantage of simplicity as the selection criterion is based on a variable that is immediately available from eddy flux measurements. In addition, when appropriate data gap-filling algorithms are used, it does not need any modeling, which could pose a problem when the data are used later for model calibration or validation.

5.4 Correction Procedures

As specified above, correction procedures are necessary at least to establish long-term budgets. In these conditions indeed, a full cover of the measurement period is needed so that underestimated fluxes should be corrected. Two correction approaches are discussed here: the u_* filtering + data gap-filling method and the advection corrected mass balance (ACMB) approach.

5.4.1 Filtering + Gap Filling

The approach consists simply in combining the filtering procedure described in Section 5.3 and a data gap-filling procedure as presented in Chap. 6. Most often the friction velocity is used as a filtering criterion. For gap filling, different methods were used, like parameterization (Goulden et al. 1996; Aubinet et al. 2000), lookup tables (Falge et al. 2001), neural networks (Papale and Valentini 2003), constrained source optimization (Juang et al. 2006) or modeling (Lavigne et al. 1997; Lindroth et al. 1998; Kutsch et al. 2008; Hutyra et al. 2008).

As based on the filtering procedure, the approach of course suffers from the same defects, as described above. Despite these flaws, this method remains the most often applied approach because of its simplicity and its relative robustness in many cases. However, some researchers are seeking for alternative filtering criteria. In particular, van Gorsel et al. (2007) proposed a filtering based on the peak sum of the turbulent flux and the change in storage. Aubinet et al. (2005) showed that this peak occurs at the beginning of the night at most sites. van Gorsel et al. (2007, 2008) argue that this is the result of the following sequence of events: After sunset, when the boundary layer becomes sufficiently stably stratified through radiative cooling of the canopy, much of the respired CO_2 is stored in the canopy, and CO_2 mixing ratios close to the ground start to increase. The cool layer within the canopy modifies buoyancy and hence the hydrostatic pressure gradient. Gravity flows start once the air close to the surface has cooled to the extent that the hydrostatic pressure gradient exceeds the sum of hydrodynamic pressure gradient and foliage drag (Finnigan 2007). Entrainment of air with a lower CO_2 mixing ratio at the hill crests leads to the development of horizontal CO_2 gradients. Once these gradients have developed advection starts to drain CO_2 out of the control volume, which results in a decrease in the sum of eddy flux and change in storage term. They hypothesize that there is a hiatus between sunset and the onset of advection during which the sum of eddy flux and storage of CO_2 may be considered as a reliable estimate of the biotic flux. They suggest, thus, keeping these measurements only and filling data gaps with one of the above-cited procedure. By applying this method to 25 tower flux sites covering a wide range of vegetation, climate, and topography, they found higher nocturnal respiration rates than estimated with u_*-threshold filter, and – where available – excellent agreement with independent estimates such as ones derived from upscaled chamber measurements (van Gorsel et al. 2009). A disadvantage of the method is that the procedure keeps very little data so that functional relationships based on these data sets are subject to large random uncertainties. Another restriction of the method is that there is no guarantee that the event sequence which is at its base takes place everywhere in all conditions. The method could thus be not applicable at some sites.

5.4.2 The ACMB Procedure

5.4.2.1 History

The ACMB (Aubinet et al. 2010) approach consists in estimating the NEE by completing eddy covariance and storage estimates by direct measurements of horizontal and vertical advection. A first attempt to estimate vertical advection was made by Lee (1998). By assuming a linear increase of the vertical velocity with height, he proposed an expression of the vertical advection based on the vertical c_c profile and on one vertical velocity measurement made at the control volume top. The advantage of this method is that it is based on a single point measurement and does not require any additional measurement. It was notably used by Baldocchi et al. (2000) and Schmid et al. (2000) to revise NEE estimations. In his reply to the Lee paper, Finnigan (1999) suggested that horizontal advection should not be neglected as it was of the same order of magnitude as the vertical advection. Following this recommendation, direct horizontal advection measurements were performed using simple single level 2D (Aubinet et al. 2003), multilevel 2D (Marcolla et al. 2005; Heinesch et al. 2007, 2008; Tóta et al. 2008), single level 3D (Staebler and Fitzjarrald 2004, 2005), and multilevel 3D (Feigenwinter et al. 2004; Sun et al. 2007; Leuning et al. 2008; Yi et al. 2008) set ups. The most advanced set up was probably those installed at three European sites in the frame of the ADVEX experiment (Feigenwinter et al. 2008). A system made up of four towers equipped each with four-point temperature, velocity, and χ_c profiles was installed at sites already equipped with eddy covariance systems. Continuous measurements were performed during 2–4 months of campaigns (Feigenwinter et al. 2010a,b). An alternative sampling system, based on continuous sampling using perforated tubing arranged parallel to the ground, was used by Leuning et al. (2008).

5.4.2.2 Procedure

The ACMB approach requires estimates of horizontal and vertical advection. Lee (1998) proposed to compute vertical advection as

$$F_{VA} = \overline{w}\left(\overline{\chi_c}\,|_{h_m} - \langle \chi_c \rangle\right) \tag{5.4}$$

where, w and $\overline{\chi_c}\,|_{h_m}$ represent the vertical component of velocity and CO_2 mixing ratio at control volume top and $\langle \chi_c \rangle$ a CO_2 mixing ratio averaged between this height and the soil. In practice, the vertical component of velocity is deduced from 3D velocity measurements performed with a sonic anemometer. In order to obtain this component, a planar-fit approach or a sectorwise planar fit is necessary, as classical 2D and 3D approaches systematically nullify w. Different methods have been proposed (Lee 1998; Paw et al. 2000; Wilczack et al. 2001), (see also Sect. 3.2.4).

Horizontal advection should require at the same time the estimation of the horizontal velocity and of the χ_c gradient in the same direction. This constitutes a strong limitation of the approach as, in sites where horizontal velocity changes often, it should require high spatial resolution χ_c samplings. In addition, these measurements should be integrated on all the control volume height, requiring in practice a multiplication of towers. In sloping sites where a sloping wind regime takes place, some authors (Aubinet et al. 2003; Marcolla et al. 2005; Heinesch et al. 2007, 2008) postulated that the wind regime was mainly 2D so that a simpler set up, based on two profiles aligned along the slope, could be used. In addition, as CO_2 build up is expected to be larger close to the soil, concentration gradients were supposed to be more important at this place and a simpler system that sampled χ_c only in the lowest layers was sometimes used. However, these hypotheses require careful verification, because also nearly uniform nighttime profiles in the canopy with largest vertical gradients near the top of the canopy were reported for a number of sites (e.g. Reiners and Anderson 1968; Goulden et al. 2006; de Araújo et al. 2008; Tóta et al. 2008; Feigenwinter et al. 2010b).

5.4.2.3 Evaluation

Unfortunately, the ACMB approach was found to give deceptive results as affected both by random and systematic uncertainties and giving nonrobust NEE estimates. Aubinet et al. (2010) showed indeed that ACMB estimates obtained at the three ADVEX sites were often one order of magnitude larger than the expected biotic fluxes and that they were not stable according to u_* changes. They found in addition that they vary with wind direction, while biotic fluxes should not vary with this variable at homogeneous sites.

Uncertainties on horizontal advection result mainly from uncertainties on horizontal χ_c gradients. Firstly, in many cases, these gradients are small and need good resolution set ups to be correctly measured. In addition, sampling point positioning is critical: as vertical gradients are generally one order of magnitude larger than the horizontal gradients, a bad vertical positioning of the sensor can lead to important systematic errors. Moreover, large horizontal gradient heterogeneities may appear in the control volume, due to source heterogeneities or to air circulation in the control volume. As a consequence, large uncertainties may also result from an insufficient spatial resolution of the χ_c sampling. Finally, in presence of large horizontal gradients that are almost perpendicular to the average wind velocity, a small error on the angle between the concentration gradient and the wind velocity could lead to erroneously large horizontal advection estimates. On the other hand, large horizontal velocities together with small horizontal gradients can also cause unrealistic high advective fluxes.

Uncertainties on vertical advection estimates are mainly due to the measurement errors that affect the vertical component of the velocity. Uncertainties relate as well to its value at the control volume top as to its vertical profile shape. Large uncertainties result notably from the computation method: none of them can be considered as better. A comparison between these methods, performed by Vickers and Mahrt (2006), pointed out significant differences between these approaches. Facing such inconsistencies, an alternative approach based on the mass continuity equation has also been proposed by Vickers and Mahrt (2006) and Heinesch et al. (2007). However, as based on an estimate of horizontal velocity divergence, it suffers from a large uncertainty, though it may be theoretically the most justified approach (Box 5.3).

Box 5.3: Recommended and Nonrecommended Correction Procedures

1. ACMB is not recommended for correcting eddy covariance measurements because
   (a) It is difficult to implement, requiring heavy set up and many workforce.
   (b) Advection measurements are affected by large random errors introducing a relative uncertainty often larger than 100% on half hourly estimates.
   (c) In most cases, huge systematic errors affect advection measurements so that ACMB lead to non realistic results even after averaging on long time periods.
2. At present, despite their different shortcomings, the filtering – gap filling approach remains the recommended correction procedure.
3. u_* is at present the most often used parameter for data selection. Criteria based on vertical velocity variance and night flux chronology are promising alternatives.

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