Inhomogeneity of the land surface and the parameterization of surface fluxes - a discussion

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Abstract

Modern measurement methods of the surface turbulent fluxes (STF) of heat, moisture and momentum in the near surface atmospheric layer by the eddy correlation method and their calculation, rely on the validity of the similarity theory of Monin-Obukhov, which requests stationarity and horizontal homogeneity. Experimental data taken at specially selected sites allowed to develop this concept. Recently performed experiments, purposely conducted in non-ideal conditions showed an underestimation of the STF values. To systematise this effect it is suggested to parameterize such underestimation as the influence of inhomogeneity and nonstationarity of the landscape and the atmosphere around the point of observation. This scheme might prove to be useful for the design of new validation experiments in non-ideal terrain.

1. Introduction
1.1 The energy balance equation on a surface under homogeneity / stationarity

There is an ongoing discussion on how to consider different types and scales of land surface inhomogeneities inside cells of models such as global climate models, as well as mesoscale models. Meanwhile several attempts were made to down- and upscale of energy and mass fluxes in the atmospheric boundary layer, based on the experimental parameterization of the interaction processes between the earth’s surface and the air flow.
Field experiments were conducted in particular areas, in most cases visually satisfying conditions of surface homogeneity. Under these conditions it was possible to use the hypotheses of stationarity and horizontal homogeneity (SHH) of the air flow and, hence, to use 1-D models of the Monin-Obukhov type for the description of the atmosphere and land surface interaction processes. Such experiments like FIFE-87 and FIFE-89 (Kanemasu et al., 1992) visually fulfilled these conditions. Therefore to determine surface turbulent fluxes (STF) the 1D-hypothesis was assumed to be valid and measurements were restricted to the vertical part of the turbulent exchange of heat and moisture. The equation of the energy balance on a surface was used in the form (Geiger, 1961; Garratt, 1992)

\[ R_n - \lambda \cdot E - H - G = 0 \]

where \( R_n \) is the net radiation flux, \( G \) is the heat flux into ground, \( H \) is the sensible heat flux, \( \lambda \cdot E \) is the latent heat flux.

Under natural conditions the land surface usually has inhomogeneities: roughness, temperature and humidity - and sometimes all simultaneously. Field experiments like KUREX and TARTEX were performed under such inhomogeneous conditions. The basic approach to determine area integrated fluxes for KUREX (Tsvang et al., 1991) and for TARTEX (Foken et al., 1993) was only slightly different to the one used for FIFE. The aggregation of fluxes from an apparently inhomogeneous surface was gained by simply adding up fluxes as derived from point measurements fully relying on the validity of the Monin-Obukhov approach of the different individual partitions of the surface.

Basically the approaches of FIFE, KUREX and TARTEX, respectively, are identical, with no net effect originating from horizontal advection. This supposition fulfilled the energy-mass exchange between the inhomogeneous, natural land surface and the atmosphere may correctly be obtained by adding up independent values of vertical surface fluxes above the homogeneous partitions inside of the total area (see Tsvang et al. (1991)).

However, it was often shown that the measured values of the turbulent fluxes did not amount to the available energy as calculated on the described 1-D way. Such an observed gap of up to some 250W/m² (s. Fig. 1 a,b; Panin, Nasonov, 1995; Laubach, 1996) in the energy balance is named herein the following as imbalance of the energy equation.

1.2. The energy balance equation including a statistical error \( \delta \)

Starting point is the equation of energy balance of a massless surface in the form:

\[ R_n - \lambda \cdot E - H - G = 0 \pm \delta \]

In principle these fluxes should add up to zero exactly, however, in experimental data a statistical error \( \delta \) has to be allowed.

The surface turbulent fluxes \( STF = \lambda E + H \) observed in nature can be calculated under SHH conditions by use of the eddy correlation method. That means to determine the
deviations of the vertical velocity $w'$, temperature $T'$ and specific humidity $q'$ from the average values $\overline{w}, \overline{T}, \overline{q}$:

$$H^{SHH} = \rho \cdot c_p \cdot \overline{w'T}, \quad \lambda \cdot E^{SHH} = \lambda \cdot \rho \cdot \overline{w'q'}$$ (3)

where $\rho$ is the density of the air and $c_p$ is the specific heat.

Every part of the energy balance equation 1 is connected with an usual sampling error - summarised in $\pm \delta$ of equation 2.

Turbulence is physically described as distribution of eddies with various sizes (spectrum of the turbulent process). Under conditions of stationarity and horizontal homogeneity the energy/mass exchange takes place between the small Kolmogorov scale, $l_0$ (molecular friction stops the turbulence of small scales or high frequencies), and the scale of the large eddies, $L_0$ (or low frequencies) extending over the whole boundary layer. This scale $L_0$ characterises the maximum size of the boundary layer eddies, participating in the vertical turbulent exchange of momentum, heat and moisture.

Structure analysis of the turbulent fluxes in stationary and horizontally homogeneous conditions (SHH) well yield estimates of $L_0$ with $L_0 \approx 250 \cdot z$, if $z$ is restricted to heights well below the top of the constant flux layer (Panin, 1985, 1990). In these SHH condition co-spectra of momentum, heat and moisture fluxes are "closed" at the high frequency edge as well as at the low frequency one (Fig. 2, Fig. 3, s. Kaimal et. al., 1972).

The magnitude of the Kolmogorov-scale

$$l_0 = (\nu^3 \varepsilon^{-1})^{\frac{1}{4}},$$ (4)

can be estimated to some $10^{-3} m$, where $\nu$ is the viscosity of air and $\varepsilon$ is the viscous dissipation rate of turbulent kinetic energy.

Analysis of field experiments like FIFE (Field et al. 1992, Fritschen et al. 1992) or KUREX and TARTEX (Foken et al., 1994) showed, that the statistical error $\delta$ is often to small to close the observed gap in the sum of the four fluxes. Moreover, the gap is of a non-statistical nature. Almost independently on the type of field experiment (i.e. Laubach, 1996), the sign of the gap shows too small turbulent fluxes.

1.3. The energy balance equation including a systematic error $\Delta$

This gap indicates the existence of a systematic error $\Delta$ besides the statistical error $\delta$. In order to account for this systematic error equation 2 is rewritten in the form

$$R_n - \lambda E^{SHH} - H^{SHH} - G = \Delta \pm \delta$$ (5)

with $\Delta$ denotes the imbalance.
Some possible reasons of systematic deficiencies can easily be detected in the equations of hydrodynamics because of the neglect of physical effects and some technical difficulties. Some parameters cannot contribute to a systematic error: \( R_n \) has a statistical error only, the error of \( G \) is small anyway.

One physical effect which was discussed in connection with the imbalance \( \Delta \) is the so-called Webb-effect (\( \bar{w} \neq 0 \)). In processes confined to a layer close to the surface the average vertical velocity \( \bar{w} \) usually is neglected. However E. Webb (1982) showed, that this neglect may not be justified in all conditions, because not \( \bar{w} = 0 \) but \( \rho \cdot \bar{w} = 0 \) is the correct assumption. Consequently the vertical fluxes change up to some percent (Bernhardt and Piazena, 1988).

Technical difficulties are connected with the spectral distribution of energy exchange and the registration of the range of high frequency part of the turbulence spectra. To measure turbulent fluctuations of velocity, temperature, humidity and other gaseous compounds of the air, devices are used which extend over a distance of \( I_{\text{min}} \approx 0.1 - 0.5 \text{m} \). This means that these devices are not set up in one point. As a consequence a gap appears between the Kolmogorov scale (\( l_\varepsilon \approx 10^{-3} \text{m} \)) and the spacing of the flux sensors \( I_{\text{min}} \). Thus the sensors neglect some parts of the spectrum (Fig.2, part 2). Such instrument spacing could become quite a source of surface fluxes underestimation because of the decrease of correlation between the high frequency fluctuations (G. Panin 1985; J. Rißmann, G. Tetzlaff, 1994).

For further discussion it is to postulate that neither the Webb-effect, nor the effect of the sensor extension, or the sum of both can explain the observed values of the total systematic imbalance \( \Delta \).

1.4 The energy balance equation under inhomogeneity / nonstationarity conditions

The purely vertical heat and moisture transfer description is valid only for the case of horizontal homogeneity (SHH). The basis for the physical description of the vertical turbulent exchange for the homogeneous condition is the similarity theory of Monin-Obukhov, containing the following assumptions (s. A. Monin, A. Yaglom, 1991):

- the vertical fluxes do not have a horizontal complement,
- the spatial properties do not impose vertical variability on the vertical fluxes.

The fluxes under SHH conditions \( STF^{\text{SHH}} = H^{\text{SHH}} + \lambda \cdot E^{\text{SHH}} \) (eq. 3) represent only the vertical component of the complete fluxes. The gradient of the other components (horizontal \( x,y \))

\[
H_x = \rho \cdot c_p \cdot \bar{u}' \bar{T}', \quad H_y = \rho \cdot c_p \cdot \bar{v}' \bar{T}',
\]

or

\[
\lambda \cdot E_x = \lambda \cdot \rho \cdot \bar{u}' q', \quad \lambda \cdot E_y = \lambda \cdot \rho \cdot \bar{v}' q',
\]  

must not be zero under conditions of inhomogeneity and nonstationarity (\( u', v' \) - deviation
of the horizontal component of the wind vector).
That means that the use of the uncompleted equations produces a systematic error.
For simplicity in stationary and horizontal homogeneity (SHH) the turbulent fluxes are
represented by $STF^{SHH}$ including the whole fluxes comprising the high frequency
contributions escaping measurements.
Then the imbalance $\Delta$ includes all the other components of the fluxes which are contained
in the complete equations to describe the turbulent transport of heat and moisture but
neglected under SHH. The amount of the Webb-effect is also included in $\Delta$. This part of
the imbalance $\Delta$ in consequence cannot be described with the assumptions of the 1-D
models.
The equation of the energy balance at a surface (eq. 5) is now rewritten in the form
\[
R_n - STF^{SHH} - G = \Delta \pm \delta
\]  
(7)
As discussed before, the energy - mass exchange in inhomogeneous conditions covers
the whole range between the Kolmogorov-scale $I_0$ and the contributions produced by
nonstationarity $L_{00}$. The numerical value of $L_{00}$ exceeds the one of the scaling feature $L_0$
resulting from Monin-Obukhov-theory (Panin, 1985). Thus the integral over the co-spectra
of the measured fluxes underestimates the real value of the fluxes due to the effect of these
lacking contributions.
The magnitude of this underestimation of fluxes in field experiments should depend on the
type of inhomogeneities and their size, the observational period and the filtering technique.
According to the described scheme the surface turbulent fluxes $STF$ in natural conditions
may be presented in form of a sum of three parts of the co-spectra (s. Fig. 2). The co-
spectral area 1 for SHH conditions as measured, can be determined by the turbulent
measurement equipment in the range from $I_{min}$ to $I_0$. The co-spectral area (2) between
the scales $I_{min}$ and $I_0$ is related to the deficiencies of the available equipment and produces
an imbalance (see point 1.3, Fig. 2). This error may be reduced using improved equipment
with smaller geometric dimensions or can be corrected theoretically (Moore, 1986). The
areas (1) and (2) represent the fluxes $STF^{SHH}$ (eq. 3) of the SHH conditions (scales from
$I_0$ to $I_0$). The area (3) of Fig.2 is the low frequency part of the co-spectrum ($STF^{LF}$)
which cannot be determined because the measurements record only the scale range from
$I_0$ to $I_0$ - the result is an imbalance $\Delta = STF^{LF}$.
As shown on Fig. 3 in measurements taken in real terrain the values of the covariance do
not approach the zero line, what they should do in SHH-conditions. The energy found in
this part of the spectrum originates from the interaction of the air flow with the surface
inhomogeneities at scales $L_{00} \geq L_0$. This co-spectrum area (3) in Fig.3 may vary
considerably according to the type of underlying surface, increasing parallel to the degree
of inhomogeneity.
Thus, turbulent fluxes measured by the eddy correlation method or by the use of 1-D
models of the Monin-Obukhov type cannot produce the full amount of vertical energy
fluxes and show as a result an energy imbalance for the inhomogen surface.
This imbalance $\Delta$ as measured or caused by a systematic error due to conceptual
deficiencies should be greater than zero in all conditions ($\Delta \geq 0$).
2. Analysis of experimental data and discussion

As an example to demonstrate the effects of the imbalances the data of three land surface experiments are more closely investigated.

These experiments are FIFE-89 (Kanemasu et al., 1992; Desjardins et al., 1992a, 1992b; Field et al., 1992; Fritschen et al., 1992), KUREX-91 (Panin, Nasonov, 1995) and TARTEX-90 (Foken et al., 1993).

The daytime variability of the components of the heat balance (eq. 5) including \( \Delta \) are shown in Fig. 1. Fig. 4 represents the dependence of the STF as taken from uncorrected measurements as a function of the available net radiation. Every point is an average over half an hour.

The STF as measured is proportional to the net radiation \( R_n \) and is systematically different for all discussed experiments. Thus, also the imbalance \( \Delta \) must be different.

The imbalance exhibited a relation to the wind speed as represented in Fig. 5a,b but also to the difference between observed infrared surface temperature and air temperature (Fig. 5c). The experimental data (Fig. 5a,b) evidence the relation of the imbalance with the wind speed. The imbalance at the surface increases with the increasing instability (Fig. 5c).

As discussed before the surface turbulent fluxes \( STF \) in natural conditions are represented as a sum of fluxes for horizontal homogeneity \( STF^{HH} \) and a flux in the low frequency range \( STF^{LF} \) which cannot be measured by a general accepted standard-method.

Standard measurement methods which allow to record the part of \( STF^{HH} \) and the \( STF^{LF} \)-part can be parametrized as an additional part of the SHH-fluxes, which are compensated for the lacking energy as summarised in \( \Delta \).

\[
STF \equiv STF^{HH} + STF^{LF} = STF^{HH} + STF^{HH} \cdot F_s = STF^{HH} \cdot k
\]  

(8)

where \( F_s \) is a correction function, \( k = 1 + F_s \) and \( F_s > 0 \).

This factor \( k \) comprises all parts of the low frequency range of the co-spectrum as an expression of inhomogeneity and nonstationarity (INH). Thus (eq.7) is transformed to

\[
R_n - G - STF^{HH} \cdot k(INH) = 0 \pm \delta,
\]

(9)

with \( STF^{HH} \) as measured in one point by standard methods (eddy correlation or based on the Monin-Obukhov-theory) in the range typically for SHH (\( I_0 \) to \( I_s \)). To quantify this factor \( k(INH) \) it can be used empirical data.

The analysis of the experiments FIFE-89, KUREX-91, TARTEX-90 show an averaged correction factor \( k \) of 1.1; 1.3 and 1.5 (Fig. 4).
3. Conclusion

Field experiments show large imbalances as measured in the energy budget $\Delta = 100 - 250 \text{ W/m}^2$ (Fig. 1). Investigation of the experimental and statistical methods shows a remaining systematic gap. The main reason of this imbalance is not the experimental methodology but conceptual deficiencies. It is related to the fact that the energy/mass exchange between the complex (horizontally inhomogeneous) land surface and the atmosphere is determined by applying theories that are based on the hypothesis of stationarity and horizontal homogeneity (SHH).

Then it must be possible to connect the observed amount of imbalance with the degree of heterogeneity of the landscape around the energy balance station. As a result of surface inhomogeneities (roughness, radiation, thermal, humidity and etc.) internal boundary layers do modify the air flow. The point observation (instrument) interprets this influences as long waves. These long frequency fluctuations become effective as process nonstationarity. For calculation of this effect it can be used some coefficient $k(INH)$ (eq. 9).

These coefficients can be interpreted as a measure of inhomogeneity.

Experimental validation requires a new experimental design. This should ensure the use of similar measuring (with the fixed beginning and ending of the measurement series) as well as directional changes of less than $5^\circ$ within the observation period. This will allow to obtain comparable $STF_{SHH}$ results at different sites of the investigated area and to achieve the required correction of the $STF_{SHH}$ values.

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References:


Fig. 1. Examples of diurnal variation of the latent heat flux ($\lambda E$), sensible heat flux ($H$), soil heat flux ($G$), net radiation ($R_n$) and the imbalance $\Delta$.

a) TARTEX-90 - (Foken et al., 1993),
b) KUREX-91 - (Panin, Nasonov, 1995).
Fig. 2. Scheme of the co-spectrum structure of the surface turbulent flux (STF) under conditions of inhomogeneity and nonstationarity.

1. part of the co-spectrum which can be measured, corresponding to the SHH conditions,
2. part of the co-spectrum related to the instrumental errors (included also under SHH),
3. part of the co-spectrum connected with the influence of the inhomogeneous underlying surface on the air flow structure ($L_0$-Kolmogorov scale, $L_{min}$-minimal scale of the STF instrumental measurements, $L_0$-Panin scale ($L_0 \equiv 250z$), $L_{oo}$-conventional scale related to inhomogeneities of the underlying surface).

Fig. 3. Examples of the heat (○) and moisture (●) fluxes co-spectra of closed (2) and unclosed (1) series according to the measurement data of the surface turbulent fluxes in FIFE-89 (site 926) by instruments of Panin and Nasonov (see Kanemasu et al., 1992).
Fig. 4. Regressions between the surface turbulent fluxes and the net radiation ($R_n$) in experiments FIFE, KUREX and TARTEX.
Fig. 5. Dependence of the normalised imbalance values on the wind velocity in 
(a) KUREX, 
(b) KUREX and FIFE, 
on the temperature differences of the soil surfaces and the air, according to the 
data of FIFE-89.