ACTA AGROPHYSICA

ATMOSPHERIC HEAT AND MASS EXCHANGE RESEARCH

pod redakcją

Bogdana H. Chojnickiego

179

**Instytut Agrofizyki
im. Bohdana Dobrzańskiego PAN
w Lublinie**

**Rozprawy i Monografie
2010 (2)**

Opiniował do druku
Prof. dr hab. Leszek Kuchar

Adres redakcji

Instytut Agrofizyki im. Bohdana Dobrzańskiego PAN, Wydawnictwo
ul. Doświadczalna 4, 20-290 Lublin, tel. (81) 744-50-61, www.ipan.lublin.pl

Streszczenia i pełne teksty prac dostępne są na stronie internetowej czasopisma
www.acta-agrophysica.org

Czasopismo jest umieszczone w następujących bazach:
Thomson Scientific Master Journal List
Polish Scientific Journals Contents – Life Sci.
Biblioteka Główna i Centrum Informacji Naukowej Uniwersytetu Przyrodniczego w Poznaniu
Instytut Bibliotekoznawstwa i Informacji Naukowej Uniwersytetu Śląskiego w Katowicach
Lonicera – serwis botaniczny

ISSN 1234-4125

Acta Agrophysica są do nabycia w dziale Wydawnictw Instytutu Agrofizyki PAN w Lublinie. Prenumeratę instytucjonalną można zamawiać w dziale Wydawnictw Instytutu Agrofizyki PAN w Lublinie oraz w oddziałach firmy Kolporter S.A. na terenie całego kraju. Informacje pod numerem infolinii 0801-205-555 lub na stronie internetowej http://www.kolporter-spolka-akcyjna.com.pl/prenumerata.asp

Wydanie I. Nakład 250 egz., ark. 10,8
Skład komputerowy: Wanda Woźniak
Druk: *ALF-GRAF*, ul. Abramowicka 6, 20-391 Lublin

This monograph was supported by:

TRANSFER of KNOWLEDGE (TOK)
in FP6
Marie Curie Host Fellowship Actions
GREENFLUX
Micrometeorological techniques for in situ measurements of greenhouse gases exchange
MTKD-CT-2006-042445
Contract No. 42445

Wojewódzki Funduszu Ochrony Środowiska
i Gospodarki Wodnej
w Poznaniu

CONTENTS

INTRODUCTION

Climate changes are currently perceived by the world of science as a serious problem which contemporary societies have to cope with. Global warming became an unquestionable fact and it is highly likely that the factors responsible for it are such as the increase of greenhouse gases in the atmosphere and the change of land use. However, while there is no consent in the world of science as to the influence of human activity on the climate on our planet, the majority of serious scientific reports confirm this hypothesis. The awareness of the consequences which the climate changes bring about, both at present and in the future, induce a better understanding of the mechanisms lying behind them as well as the essence of the processes influencing climate. It is equally important to recognize the consequences of climate changes both on a global and a local scale. Thus, it is not surprising that the intellectual effort of the world of science is directed mostly towards examining the above processes. If we want to know how to protect climate from these changes we must answer the question of 'How does the existence and functioning of particular ecosystems influence the global balance of heat and greenhouse gases exchanged between the surface and the atmosphere?'

The research which will lead to answering the question formulated above must, by nature, be multidirectional and include a whole range of issues concerning mass and energy exchange. Such research, due to its complex nature, must be conducted over the surfaces of various elements of the landscape, so that in the future it would be possible to create models which will allow estimating energy and matter balances for big areas (region, country or continent).

The following monograph addresses a whole array of issues connected with mass and energy exchange between various components of the landscape and the atmosphere. The problems presented here focus mainly on greenhouse gases exchange (water vapor, carbon dioxide and methane), some chapters are devoted to the influence of meteorological conditions on the concentration of other gases over urban areas (ozone and radon). Six chapters included in the monograph have been written by the faculty of the Meteorology Department of Poznań University of Life Sciences (PULS) together with co-authors from other foreign research institutes (University of Helsinki (UH), Technical University in Munich (TUM), and the Liebniz-Centre for Agricultural Landscape and Land Use Research (ZALF). The remaining three chapters have been written by scientists from the following institutions: University of Łódź, Institute of Nuclear Physics of the Polish Academy of Sciences and Warsaw University of Life Sciences.

The Department of Meteorology of Poznań University of Life Sciences (PULS) is one of the few units in Poland whose activities have for almost thirty years focused on examining the structure of heat balance of active surfaces in various ecosystems and, currently, mainly on the estimation of greenhouse gases balance in ecosystems. During that time, the emphasis has been placed particularly on the development of modern research facilities to measure the flux of greenhouse gases exchanged between the active surface and the atmosphere. In the 1990s the team from the Department of Meteorology (since 2009 Agrometeorology) carried out research with the use of the profile method and the heat balance method while measuring mass and energy fluxes over various ecosystems at different latitudes in Europe and Asia. Thanks to effectively developed international cooperation, a new measuring station was established in 2003 in the peatland in Rzecin which was subsequently included in the European consortium set up within the 6th CarboEurope-IP Frame Program. The first station in Poland which was established then for ongoing measurements of energy and greenhouse gases (CO_2, H_2O) fluxes over the land ecosystem by means of the eddy covariance method, became one of the most important measurement stations within the European network of measurement stations of the CarboEurope Project. In 2006, thanks to the extensive equipment facilities of the station, the Department of Meteorology entered another European consortium established within the NitroEurope-IP project. As a consequence, Rzecin station was equipped with new sensors and measurement facilities which largely extended the range of measuring techniques (e.g. by including automatic chambers for methane flux measurements and CO-TAG system for measuring fluxes of such gases as ammonia). However, NitroEurope project includes not only Rzecin station. The joint efforts of research teams of the Department of Meteorology of PULS and the research team from the Institute of Landscape Dynamics, Liebniz-Centre for Agricultural Landscape and Land Use Research (ZALF) led to establishing two common manipulation experiments in Paulinenaue and in Zarnekow, Germany. These two experiments attempt at answering the question how the change of the method of land use may influence the dynamics of nitrogen and carbon in soil and mostly the scale of gas exchange between the surface of the ecosystem and the atmosphere. As a result of the advanced international cooperation, already in 2006 the Department of Meteorology began the implementation of another project within the 6th Marie Curie Actions Frame Program, of a Transfer of Knowledge type. The project, whose acronym is GREENFLUX, intensified international scientific cooperation of the Department of Meteorology which led to trainings of the scientists from Department of Meteorology at the University of Helsinki and at the Technical University in Munich as well as at the ZALF Müncheberg mentioned above. The transfer of knowledge and experience conducted within the project led to importing to Poland chamber techniques for measuring greenhouse gases fluxes and to the development and construction of the Relaxed Eddy Accumulation (REA), for measuring the fluxes of trace gases (e.g. CH_4) exchanged between the surface of the ecosystem and the atmosphere, which was the first such system in Poland and one of the few in Europe. All the achievements mentioned above made the team from the Department of Meteorology an internationally recognized research unit focusing on examining mass and energy fluxes over various ecosystems, both in Poland and abroad. While developing the measurement network, in 2008 the Department of Meteorology built the first measurement tower in Poland for the fluxes of CO_2 and H_2O measured by means of the eddy covariance technique over the pine forest in Tuczno. The station was established in cooperation with the Central Administration of State Forests. The research results stemming from the projects mentioned above as well as the detailed description of the methods of mass and energy fluxes exchanged between the active surface and the atmosphere can be found in relevant chapters of the following monograph (chapters 1, 2, 3, 7, 8 and 9).

The subsequent chapters of the monograph introduce the description of measuring techniques and the results of measurements of mass fluxes and gases concentration over urban areas. Particular attention of the reader should be drawn to the work of the team of the Department of Meteorology and Climatology of the University of Łódź which conduct the research into mass and energy fluxes exchanged over a city area, a pioneering study for Poland (chapter 4). Similarly, the work conducted by two cooperating teams, one from the Department of Meteorology and Climatology of the University of Łódź and the other from the Institute of Nuclear Physics of the Polish Academy of Sciences, is very original, as well as the work by the Department of Meteorology and Climatology of Warsaw University of Life Sciences focusing on the influence of meteorological conditions on the gas exchange (radon and ozone) including the phenomenon of the ozone smog in the city (chapters 5 and 6).

All the issues described above have been presented in the monograph as a coherent whole, in the hope that it will bring a significant contribution to Polish scientific research into the mass and energy fluxes exchanged between various surfaces and the atmosphere, particularly in the context of research into climate change and its prevention.

Prof. dr hab. Janusz Olejnik

1. THE MASS AND ENERGY EXCHANGE IN THE SURFACE LAYERS OF THE SOIL AND ATMOSPHERE

Jacek Leśny, Janusz Olejnik

Meteorology Department, Poznan University of Life Sciences
ul. Piątkowska 94, 60-649 Poznań, Poland
e-mail: jlesny@up.poznan.pl

INTRODUCTION

The matter and energy exchange processes in the surface layers of the atmosphere and soil are the important part of a continuous circulation of matter and energy flows taking place on the globe. This issue has been dealt with for a long time because of its importance for understanding the physical processes shaping environmental conditions (Brutsaert 1988, Cole 1975, Iribarne and Cho, 1988, Johnson 1954, Kanemasu *et al*. 1979, Kędziora 1994,1995, Landsberg 1985, Monteith 1975, 1976, 1977, Oke 1978, Olejnik, 1988, 1996, Oliver 1981, Riehl 1978, Rosenberg *et al*. 1993, Sorbjan 1983). Exchange processes may occur by means of conduction (energy only), diffusion and turbulent exchange. In the general balance the first two actually do not count because of their very low efficiency. In principle, as far as the environment is concerned only turbulent exchange is noticeable. It is very important to link mass exchange with the exchange of energy occurring as a result of water phase transitions. Evaporating water requires very large portions of energy which is then transferred in a turbulent way to the place where the water condensation occurs. One could say that this property of water is vital for establishing the energy balance) and as a consequence the thermal conditions prevailing on the Earth's surface and in the atmosphere. Unfortunately, exchange processes are not as easily measurable as standard meteorological parameters. Various methods are used in research practice, some of the most frequently used ones are the profile method and Bowen balance method. The theoretical basis of the two methods has been known for a long time (Bowen, 1926, Johnson 1954, Kanemasu *et al*. 1979, Monteith 1975, 1976, 1977, Oke 1978), but the high technical requirements limited the possibility of their application . Only the intensive development of electronics popularized these methods, however, the requirements which the measurement equipment has to meet and the area over which the measurements have to be performed cause that they will probably never be standard measurements of meteorological stations, and always will be carried out by specialist research campaigns.

MOMENTUM EXCHANGE IN THE BOUNDARY LAYER OF THE ATMOSPHERE

When considering the process of evaporation from the active surface (exchange of mass and energy) and the active surface heat exchange with the atmosphere (energy exchange), particular attention should be paid to the layer lying close to the ground and reaching the height of not more than a dozen meters above the canopy level (Kędziora 1995). In literature the name boundary surface layer (Monteith 1975) has been adopted. There is a thin (the order of a millimeter) laminar layer adjacent directly to the ground . The main mechanism of mass and energy transfer in the laminar layer is molecular diffusion, while in the boundary layer - turbulence. The movement of the air in the boundary layer is very irregular (as opposed to the upper atmosphere) and consists of fluctuations in the form of turbulences and "air bubbles". Small fluctuations and high frequency turbulences are caused by the friction against the base ground surface and by the air viscosity. Larger, more rarely occurring disturbances caused by the heat variations in the surface layers of the air are superimposed on those fluctuations, which results in the creation of outflow hydrostatic forces - warmer air rises up. The laminar layer of the atmosphere is separated from the base ground by the active surface. Every surface through which a process of mass and energy flow occurs, simultaneously with their transformation, is called the active surface (Kędziora 1995, Molga 1986, Rosenberg 1974). For example, the soil layer is an active surface, since the gas exchange (water vapor and other gases) between the atmosphere and the soil takes place through it. Soil absorbs short-wave solar radiation and emits long wave radiation. Mass and energy exchange processes which are the most important for the life of various ecosystems occur in the atmospheric boundary layer. This exchange is of course multidirectional, but this paper is focused on the exchange in the vertical direction, from the active surface to the atmosphere or vice versa.

The closer to a surface, the lower is the velocity of air movements which eventually reaches zero near the surface. Of course, the vertical velocity profile depends on the type of a surface over which air movements take place. It looks different over a smooth surface, such as an ice floe, or a road, and different over more rough surfaces, such as a forest, a corn field or a meadow. As a result of a decrease in the wind velocity in the direction of the active surface, there must be a momentum flux transferred in the same direction from the upper layers of the atmosphere downwards. At the same time the moving air takes the matter in the gaseous form (including water vapor, CO_2) or heat from the active surface or passes such matter to it . It should be noted, however, that momentum is always transferred in the direction of velocity drop, which means that it will be transferred from the air to the active surface, while heat energy and water vapor can be exchanged in both directions.

The momentum exchange must be considered as a basic process determining other flow processes, especially the flow of heat and water vapor. It results from the fact that even in the air with a uniform temperature and uniform composition, if there are differences in velocity, the momentum will be exchanged. There are two types of air movements over any surface. This may be a laminar flow, also called layered, when the air moves by distinguishable layers not intermixing with each other. The second type is a turbulent movement, occurring as a result of friction in the flowing air, which causes a number of distortions in the shape of small eddies . Air flow in the surface layer may occur in two ways. The more rough surface and the higher speed of motion, the more likely that movement will have a turbulent nature. Moreover, if the initially laminar flow will turn into a turbulent one, then even a significant decrease in the speed and for example smoothing of the surface, will not easily cause the transition back into the laminar motion. Due to the strong mixing in the turbulent flow the exchange rate of momentum, heat energy and water vapor is 10 000 times greater than in the laminar motion. Summarizing, it can be concluded that the only important factor for the exchange processes in the natural environment is the turbulent motion and the laminar movement can be completely disregarded with no harm to the quantitative descriptions (Kanemasu 1979).

The value of the momentum flux depends primarily on the wind velocity gradient in the surface layers of the air and on the roughness of the surface itself. In turn, the momentum flux is a measure of the efficiency of the turbulent transfer of other components, such as heat energy, water vapor, carbon dioxide and other (Kędziora 1995, Desjardis *et al*. 1992).

VERTICAL WIND VELOCITY PROFILE

The pace of the vertical mass and energy exchange depends largely on the thermodynamic equilibrium state of the air. In the unstable equilibrium state the hydrostatic outflow forces predominate, in the steady equilibrium state the forces damping the vertical exchange prevail and in the neutral equilibrium state there is a balance between these forces.

The neutral equilibrium state in the atmosphere is assumed at the beginning in order to obtain a simple description. Assuming that the wind velocity at the active surface is zero, and already at the height of several meters above the surface the velocity is little variable with the change in altitude, the vertical distribution of wind velocity can be described by the equation:

$$u(z) = A \cdot \ln z + B \tag{1}$$

where: $v(z)$ – average wind velocity at the height z ,

A and B – coefficients independent of height.
Lets $B = -A \cdot \ln z_0$, then:

$$u(z) = A \cdot \ln(z / z_o) \tag{2}$$

From the analytical considerations and field experiments it follows that

$$A = \frac{v_*}{k}, \tag{3}$$

where: k = 0,41– experimentally determined von Karman constant, v_* – a value called dynamic or friction velocity(Kanemasu i in. 1979, Monteith 1975, Sorbjan 1983).

From the equations (2) and (3) it follows that:

$$v(z) = \frac{v_*}{k} \ln \frac{z}{z_o} \tag{4}$$

For a given wind velocity at the height z the dynamic velocity v_* will be greater over the more rough surface than over the smooth surface, and thus, the effectiveness of turbulent exchange over various surfaces will depend on their roughness, i.e. on the parameter z_o.

The discussed case relates to a smooth surface (without plants) with small roughness z_o. When considering the air flow over the vegetation, the wind profile is much more complicated. Only in the area above the vegetation canopy the wind profile is logarithmic. In order to describe the vertical wind profile over the area covered with vegetation by means of the logarithmic equation (4), a certain value d should be deducted from the height z. The d value is called the height of zero plane shift. This means that the value of wind velocity is not measured from the ground surface, but from the plane shifted from the ground by the distance d.

Equation (4) takes the form:

$$v(z) = \frac{v_*}{k} \ln \frac{z - d}{z_o} \tag{5}$$

and is valid only for the height z greater than the plants height. The values of z_o and d are functions of the plants heights. In most cases, they can be calculated from the following equations (Oke 1978):

$$0.1 \cdot h < z_o < 0.15 \cdot h \tag{6}$$

$$d = 2/3 \cdot h \tag{7}$$

where: h – plants height.

Vertical wind profile over a homogeneous flat surface remains in dynamic equilibrium with the surface. So when the nature of the groundchanges, e.g. the wind blows from a mown meadow to a corn field (here the problem of the landscape structure arises), then when crossing the border of the two complexes its profile undergoes a distortion and transformation. What is needed it is some distance from the edge of the fields on which the wind will gain a new dynamic equilibrium with the ground and on which a new vertical wind profile will be formed.

This distance is called the **fetch requirement** and is essential for the selection of the place for wind velocity measurements. Over the new surface the **internal boundary layer** is generated which is in the dynamic equilibrium with it only on a certain, short distance from the surface. The thickness of this sub-layer, to which the principle of fixed flow applies and in which the flux momentum of heat, water vapor, etc. is independent of the altitude, can be defined by the following equation:

$$\delta(x) = 0{,}1 \cdot x^{0{,}8} \cdot z_o^{0{,}2} \tag{8}$$

where: x – a distance from the border between the two types of surfaces, z_0 – a new surface roughness parameter.

For example, in the distance of 100 meters from the beginning of a corn field of 1.5 m (z_0 = 0.15) height, there is only a 3-meter layer of air above the field when walking with the wind, and within this layer the streams are constant and independent of altitude The anemometers for measuring the appropriate wind profile should be placed in this very layer.

MOMENTUM, HEAT AND MASS (WATER VAPOR) FLUXES BETWEEN AN ACTIVE SURFACE AND THE ATMOSPHERE

Examining the phenomenon of energy and mass transfer in the boundary surface layer one should remember about the following two principles:

1. Flux density of any value passing through the given environment at each point is directly proportional to the concentration gradient of the value causing this flow.
2. Flux density of any value passing through the given environment between two points is directly proportional to the concentration difference of the value causing the flow between these two points and inversely proportional to the resistance which the environment creates to the passing flux.

These principles explain fairly well the equations presented below which account for vertical momentum flux density, apparent heat and heat used for the evaporation which is equivalent of the water vapor flux density exchanged between the atmosphere and the active surface.

Using the rule (1) and the concept of turbulent exchange coefficient (K), one obtains:

$$\tau = \rho \cdot K_M \frac{\partial v}{\partial z}, \tag{9}$$

$$E_t = -\rho \cdot K_V \frac{\partial q}{\partial z}, \tag{10}$$

$$S = -\rho \cdot c \cdot K_H \frac{\partial T}{\partial z}. \tag{11}$$

At the same time using rule (2) and the coefficient of aerodynamic resistance ($r_{a,M}$), we obtain:

$$\tau = \rho \cdot \frac{v(z)}{r_{a,M}}, \tag{12}$$

$$E_t = \rho \frac{q(z) - q(0)}{r_{a,V}}, \tag{13}$$

$$S = \rho \cdot c \frac{T_a - T_s}{r_{a,H}}, \tag{14}$$

where in formulas (9) – (14) following notation is used:
ρ – air density (1.2 kg m^{-3}),
c – specific heat of air (1004 J $kg^{-1}K^{-1}$),
K_M, K_V, K_H, – diffusivity coefficients of momentum, water vapor and heat ($m^2 s^{-1}$),
$r_{a,M}$, $r_{a,V}$, $r_{a,H}$ – aerodynamic resistance coefficients, respectively for momentum, water vapor and heat respectively (s m^{-1}),
$\partial v/\partial z$ – vertical gradient of wind velocity (s^{-1}),
$\partial q/\partial z$ – vertical gradient of specific moisture (m^{-1}),
$\partial T/\partial z$ – vertical gradient of air temperature (K m^{-1}),
$v(z)$ – wind velocity on the measurements level (z) (m s^{-1}),
$q(z)$ – specific moisture on the measurements level (z) (kg kg^{-1}),
$q(0)$ – specific moisture on the active surface, (kg kg^{-1})
T_a – air temperature on the measurements level (z) (K),
T_S – temperature of the active surface (K),
τ – momentum flux density (N·m^{-2}),

E_t – flux density of water vapor (kg $m^{-2}s^{-1}$),
S – heat flux density (W m^{-2}).

In the quantitative description of the exchange processes of energy and mass in the boundary layer one uses the similarity theory, which says that the coefficients of turbulent exchange of momentum, heat and mass are equal under the neutral equilibrium conditions in the atmosphere:

$$K_M = K_V = K_H \tag{15}$$

or that the aerodynamic resistance coefficients of momentum, heat and matter fluxes between the level z_1 and z_2 are equal in the neutral equilibrium conditions:

$$r_{a,M}(z_1, z_2) = r_{a,V}(z_1, z_2) = r_{a,H}(z_1, z_2) \tag{16}$$

where the indexes M, V, H refer to the momentum, water vapor and heat respectively.

Transfer coefficient (in turbulent exchange) of any physical value Q in the given liquid medium K_Q can be defined as the ratio of this value flux density (Q $m^{-2}s^{-1}$) to the concentration gradient of this magnitude (Q m^{-3} m^{-1}). As a result, the K_Q coefficient has a dimension of area/time (m^2 s^{-1}). This ratio is also called diffusivity.

The equations from 9 to 14 are not suitable for practical measurements of the fluxes exchanged with the active surface until the coefficients K and r are not unraveled. Therefore, the following section is devoted to the presentation of the method of transformation of these equations so that they can be applied in practice.

If the flow is of a stabilized character, which means that the flux values in this layer are constant then the calculations are done using the first set of equations for the developed boundary layer. The gradient value of the quantity causing the flow is a function of height. Gradient decreases in inverse proportion to the height (the derivative of equation 5). Therefore, as it follows from equations 9 to 11, the coefficients K have to grow with the height to ensure the fluxes stability.

Specific humidity of the air (q) in the equation 10 has been replaced by the water vapor pressure (e) since its value is more often applied. A simplified relationship between the two values has been used:

$$q = \frac{\varepsilon}{p} e, \tag{17}$$

where:
p – atmospheric pressure (hPa),
ε – ratio of molecular weights of water vapor and air which is equal to 0.622.

After this substitution equation 10 took the form of:

$$E_t = -\frac{\rho_a \cdot \varepsilon}{p} \cdot K_V \cdot \frac{\partial e}{\partial z} \tag{18}$$

Integrating the equations 9, 18 and 11 in the range of z_1, z_2 and converting the formula, one obtains the following equation:

$$\tau = -\rho \cdot K_M \cdot \frac{v_2 - v_1}{z_2 - z_1} \tag{19}$$

$$E_t = -\frac{\rho \cdot \varepsilon}{p} \cdot K_V \cdot \frac{e_2 - e_1}{z_2 - z_1} \tag{20}$$

$$S = -\rho \cdot c_p \cdot K_H \cdot \frac{T_2 - T_1}{z_2 - z_1} \tag{21}$$

Using equation 5 for the heights z_1, z_2 one receives:

$$v_2 - v_1 = \frac{v_*}{k} \cdot \ln \frac{z_2}{z_1}$$

After squaring this equation and using the definition of v_* given by the equation (Monteith 1975, Schwerdtfeger 1976):

$$v_*^2 = \frac{\tau}{\rho_a}, \tag{22}$$

and using equation 19, we received:

$$K_M = \frac{k^2 (v_2 - v_1)(z_2 - z_1)}{(\ln \frac{z_2}{z_1})^2} \tag{23}$$

Given that the vertical gradients of wind velocity, vapor pressure and temperature are inversely proportional not to the height z over the active surface, but to the z – d, where d is the height of zero plane shift, using equation 23, and the theory of similarity, one can formulate definitive forms of the equations for momentum, water vapor and heat fluxes that are exchanged between the two levels in the atmosphere under the conditions of the stationary flow. They allow the calculation of the density values of these fluxes on the basis of wind velocity, vapor pressure and temperature measurements only on two levels:

for momentum
$$\tau = \rho \cdot \left[\frac{k(v_2 - v_1)}{\ln \frac{z_2 - d}{z_1 - d}} \right]^2 \tag{24}$$

for water vapor
$$E_t = -\frac{\rho \cdot \varepsilon \cdot k^2 (v_2 - v_1)(e_2 - e_1)}{p(\ln \frac{z_2}{z_1})^2} \tag{25}$$

for heat
$$S = -\frac{\rho \cdot c \cdot k^2 (v_2 - v_1)(T_2 - T_1)}{(\ln \frac{z_2}{z_1})^2} \tag{26}$$

The flux of water vapor flowing from the active surface of the atmosphere can be expressed as an energy flux needed to evaporate water in the process of evapotranspiration (LE), because this process is a source of water vapor flowing into the atmosphere. This energy flux is equal to the product of the water vapor flux E_t and the latent heat of evaporation *LE*. After replacing the water vapor flux E_t with the energy flux *LE* equation 10 takes the following form:

$$LE = -\frac{L \cdot \rho \cdot \varepsilon}{p} K_V \frac{\partial e}{\partial z} \tag{27}$$

introducing coefficient γ (psychrometric constant) defined by the formula:

$$\gamma = \frac{c \cdot p}{L \cdot \varepsilon} \tag{28}$$

one obtains after transformation:

$$\frac{L \cdot \varepsilon}{p} = \frac{c}{\gamma}$$

and ultimately the equation 27 takes the form:

$$LE = -\frac{\rho \cdot c}{\gamma} K_V \cdot \frac{\partial e}{\partial z} \tag{29}$$

Together with the equation 2.11

$$S = -\rho \cdot c \cdot K_H \frac{\partial t}{\partial z}$$

they create a pair of equations, which express the density of latent and apparent heat fluxes flowing from the active surface to the atmosphere under the conditions of the stationary flow and the neutral equilibrium of the atmosphere. As already mentioned, these equations can be applied only after coefficients K_v and K_H are unraveled. To accomplish this, the equations for the vertical profile of wind and the friction velocity v_* are used.

Differentiating equation 2.5 and using equations 22 and 9, after the transformations one obtains:

$$K_M = k^2 \cdot (z-d)^2 \cdot \frac{\partial v}{\partial z}$$

Using again the similarity theory, by substituting K_M in the place of K_V and K_H one finally gets a couple of equations to calculate latent and apparent heat flux densities in the developed boundary layer. They take the following forms:

$$LE = -\frac{\rho \cdot c}{\gamma} \cdot k^2 \cdot (z-d)^2 \cdot \frac{\partial v}{\partial z} \cdot \frac{\partial e}{\partial z}, \qquad (30)$$

$$S = -\rho \cdot c \cdot k^2 \cdot (z-d)^2 \cdot \frac{\partial v}{\partial z} \cdot \frac{\partial T}{\partial z}, \qquad (31)$$

which are frequently used in the measurement practice. It should be noted, however, that one can use them only under the conditions of neutral equilibrium in the atmosphere (possible vertical movements of the air are not caused by the thermodynamic forces). In another situation (unstable or stable equilibrium) equations are becoming even more complicated, which is presented in the following section.

THE EFFECT OF AN ATMOSPHERE THERMODINAMIC EQUILIBRIUM ON THE EXCHANGE OF ENERGY AND MOISTURE IN THE DEVELOPED BOUNDARY LAYER OF THE ATMOSPHERE

In the previous section, all equations concerned the neutral equilibrium in the atmosphere. Considerations on the impact of the atmosphere on the momentum, vapor and heat fluxes should be started by identifying the thermodynamic equilibrium state of the atmosphere. For this purpose, the concept of Richardson number has been introduced, expressed by the formula:

$$Ri = \frac{g}{t} \cdot \frac{\partial\theta / \partial z}{[\partial v / \partial z]^2} \qquad (32)$$

where: $\partial\theta / \partial z$ – vertical gradient of potential temperature (K m^{-1}).

When the values of temperature and wind velocity are known only on the two levels, then the Richardson number (*Ri*) is expressed by the formula:

$$Ri = \frac{g}{t} \cdot \frac{(\theta_2 - \theta_1) \cdot (z_2 - z_1)}{(v_2 - v_1)^2}. \qquad (33)$$

In the ground layer one the potential temperature θ can be replaced by the actual temperature *t*. In the unstable equilibrium the value of Richardson number is less than zero, in the stable equilibrium Ri is bigger than zero.

After considering the impact of atmospheric thermodynamic equilibrium the equations 30 and 31 take the following form:

$$LE = -\frac{\rho \cdot c}{\gamma} \cdot k^2 \cdot (z-d)^2 \cdot \frac{\partial v}{\partial z} \cdot \frac{\partial e}{\partial z} \cdot (\Phi_V \Phi_M)^{-1}, \qquad (34)$$

$$S = -\rho \cdot c \cdot k^2 \cdot (z-d)^2 \cdot \frac{\partial v}{\partial z} \cdot \frac{\partial T}{\partial z} \cdot (\Phi_H \Phi_M)^{-1}. \qquad (35)$$

Where: Φ_M, Φ_V, Φ_H are the functions of atmospheric stability, for momentum, water vapor and heat respectively.

In the last 20 years a number of empirical functions of stability have been developed. Most frequently, the following equations are used:

when Ri>0 steady equilibrium state

$$\Phi_H = \Phi_V = \Phi_M = (1 - 5R_i)^{-1}, \qquad (36)$$

when Ri<0 unstable equilibrium state

$$\Phi_H = \Phi_V = \Phi_M^2 = (1\text{-}16 \cdot R_i)^{-0.5}. \qquad (37)$$

Assuming, according to the similarity theory, the compatibility of Φ_H and Φ_V one can formulate a function of the thermodynamic equilibrium state impact on the vertical exchange of mass and energy:

$$F = (\Phi_{V,H} \cdot \Phi_M)^{-1}$$

and using equations 36 and 37, one obtains:

for *Ri* > 0 stable equilibrium state

$$F = (1 - 5R_i)^2 \qquad (38)$$

Ri < 0 unstable equilibrium state

$$F = (1 - 5R_i)^{0.75} . \tag{39}$$

If the atmosphere is in unstable equilibrium, then the proposed function F increases the momentum, water vapor and heat fluxes. Otherwise, the stable equilibrium decreases fluxes.

The equations 34 and 35 enable the determination of the energy fluxes used for evaporation and heating of the air when vertical profiles of temperature, vapor pressure and wind are known. Therefore, using the results of the measurements and the aforementioned set of equations one can obtain the two most difficult to measure components of the heat balance of the active surface.

BOWEN METHOD

Generally it has been accepted to express the equation of the heat balance of the active surface in the following form (Paszynski 1972, Monteith 1975, Oke 1978):

$$Rn + LE + S + G = 0 \tag{40}$$

where: *Rn* – radiation balance (W m^{-2}),
LE – latent heat flux density (heat consumed in evaporation) (W m^{-2}),
S – apparent heat flux density (heat consumed in heating of the air) (W m^{-2}),
G – soil heat flux density (W m^{-2}).

It is assumed that the individual components of the equation 40 take positive values, if they represent the energy inflowing fluxes to the active surface, and negative if they represent fluxes of energy flowing out from the active surface.

It is relatively simple to measure the balance of radiation (*Rn*) and soil heat flux (*G*). Sensors used for such measurements are available and are often used at meteorological stations. Using the results of the measurements of these parameters allows for the estimation of the individual components of the heat balance, using the so-called Bowen's method. This name derives from the fact that the ratio of apparent heat flux density to the latent heat has been adopted as the Bowen ratio (β):

$$\beta = \frac{S}{LE} . \tag{41}$$

The values of the turbulent heat balance components can be determined on the basis of the above equation (41) and by transforming the equation 40. Then one obtains the following:

$$LE = -\frac{Rn + G}{1 + \beta}, \tag{42}$$

$$S = -\frac{Rn + G}{1 + \frac{1}{\beta}}. \tag{43}$$

This method for assessing the apparent and latent heat is called the Bowen heat balance method. If now, one substitutes the equations (34) and (35) for the equation (41) the following relationship is obtained:

$$\beta(z) = \gamma \cdot \frac{\frac{\partial t}{\partial z}}{\frac{\partial e}{\partial z}}. \tag{44}$$

Thus, as seen above there is no need to include the functions of the atmosphere thermodynamic equilibrium in the Bowen's method. In general one measures the values of temperature and water vapor pressure on two levels and then, just as in the profile method using the Lagrange theorem replaces gradients with the differences quotient in the equation (44). Unfortunately, this approach involves the risk of committing an error, especially in the case of a non-linear changes in gradients t and e at the active surface. Another way to proceed is to measure the abovementioned parameters on several levels, then to set a function of the parameters variability with the height and, in consequence, to determine the actual temperature and vapor pressure gradients (Olejnik 1996, Forest 1998).

Exploiting the differences requires the use of more accurate sensors, since even a small error (deviation) of one sensor can strongly affect the value of the determined heat balance components. Determination of the vertical variation function requires more sensors, but the calculation process allows eliminating questionable readings maintaining the accuracy of the final results.

CONCLUSIONS

In summary, in order to apply the profile method to assess the heat flux used in water evaporation and for warming up the air, one needs to know the vertical profiles of wind, temperature and vapor pressure. A shortcoming of this method is the eventuality that the heat balance of the active surface will not be struck, i.e., the sum of all fluxes will not give 0 value in result, as it should stem from the equation (40). Such situation implies the occurrence of inaccuracies or errors in the measurements, but unfortunately it does not give the answer which of the components was wrongly calculated. On the other hand, obtaining zero result for the sum of these components gives the investigator high confidence that the measurement process was conducted properly, and the obtained results are very close to reality.

The Bowen's method, to some extent by definition, satisfies the equation (40). It does not require the information about the wind speed profile over the active surface, which greatly simplifies the measurement system and reduces the number of sensors. However, it also has some drawbacks. Equations 42 and 43 indicate that when the Bowen ratio is close to –1 the determined fluxes may drastically differ from the real ones. For example: the results may indicate that there is a huge condensation of water vapor, and the heat emitted by it is warming the air, or conversely, that the great flux of energy from the air is used in the evaporation. Both situations are absurd, but the uncritical treatment of the results may lead to such errors.

To avoid them, one should notice that the Bowen ratio approaches the value of –1 if the temperature gradients have opposite signs and the absolute value of the vapor pressure gradient roughly equals 0.6 of the temperature gradient. It occurs most often during the redirection of energy fluxes flow, i.e. during sunrise and sunset. Generally, all components of the heat balance take then the values close to 0. Then the temperature and vapor pressure gradients are also very low, which means that a researcher often reaches the limits of the sensors' accuracy, therefore, even if the determined gradients are close to the actual ones, their ratio and as a consequence also the Bowen ratio can vary significantly from the real value. Since, as it has been mentioned before, the values of the energy fluxes are low during these periods they are often skipped in the calculations, and the fluxes' values are interpolated on the basis of their daily courses. This procedure seems to be burdened with a smaller error than the determination of the fluxes using formulas 42 and 43 at all costs, and in the case when a researcher is seeking to obtain the average daily values of heat balance components the possible error is negligible.

REFERENCES

Bowen, I.S., 1926. The ratio of heat losses by conduction and by evaporation from any water surface. Physics Review, 27, 779-787.

Brutsaert W., 1988. Evaporation into the Atmosphere. Theory, History, and Applications. D. Reidel Publishing Company, Dordrecht.

Cole F., 1975). Introduction to meteorology. John Wiley & Sons, Inc., New York.

Desjardis R.L., Schuepp P.H., MacPherson J.I., Buckley D.J., 1992. Spatial and temporal variation of the fluxes of carbon dioxide and sensible and latent heat over the FIFE site. J. Geo. Res., 27, D17, 18467-18475.

Iribarne J., Cho H., 1988. Physical of atmosphere(in Polish). PWN, Warszawa.

Johnson J., 1954. Physical Meteorology. John Wiley & Sons.

Kanemasu E.T., Wesely M.L., Heiman J.L., 1979. Techniques for calculating energy and mass fluxes. In: B.J. Barfield & J.F. Gerber (eds), Modification of the aerial environment of plants. Am. Soc. of Agric. Engineers, St. Joseph Michigan USA, 156-182.

Kędziora A., 1994. Micrometeorological and remote sensing methods used in environmental investigation. Zesz. Probl. Post. Nauk Roln., 405, 101-114.

Kędziora A., 1995. Principles of agro meteorology (in Polish). PWRiL, Poznań.

Landsberg H.E., 1985. World Survey Climatology. Elsevier, Amsterdam.

Leśny J., 1998. Analysis impact of plant canopy to the structure of heat balance of active surface (in Polish). PhD thesis, Library of Poznan University of Life Sciences.

Molga M., 1986. Rural meteorology (in Polish). PWRiL, Warszawa.

Monteith J.L., 1975. Vegetation and the atmosphere. Vol.1, Acad. Press, London.

Monteith J.L., 1976. Vegetation and the Atmosphere. Vol. 2. Academic Press, London.

Monteith J.L., 1977. Physical of biological environment. PWN, Warszawa.

Oke T.R., 1978. Boundary layer climates. Methuen & Co LTD, New York: 372.

Olejnik J., 1996. Catchment scale modeling of heat and water balance structure under present and future climatic conditions (in Polish). Roczniki Akademii Rolniczej w Poznaniu, 268.

Olejnik J., 1988. The empirical method of estimating mean daily and mean ten-day values of latent and sensible-heat near the ground. J. Appl. Meteorol., 12, 1358-1369.

Oliver J., 1981. Climatology: Selected Applications. V. H. Winston & Sons, Edward Arnold, London.

Paszyński J., 1972. Studies on the heat balance and on evapotranspiration. Geogr. Pol., 22. 35-51.

Riehl H., 1978. Introduction to the Atmosphere. McGrow – Hill Book Company, New York.

Rosenberg N.J., 1974. Microclimate: the biological environment. Wiley, New York.

Rosenberg N.J. (ed.), 1993. “Towards an Integrated Impact Assessment of Climate Change: The MINK Study", Climatic Change, (Special Issues), 24, 1-173.

Schwerdtfeger P., 1976. Physical principles of micro-meteorological measurements, Amsterdam, Oxford [etc.]: Elsevier, 113.

Sorbjan Z., 1983. Turbulence and diffusion in lower atmosphere (in Polish). PWN, Warszawa.

2. ESTIMATION OF NET CARBON AND WATER EXCHANGE AT A SCOTS PINE FOREST STAND IN POLAND*

Marek Urbaniak, Bogdan H. Chojnicki, Alina Danielewska, Marcin Baran, Janusz Olejnik

Meteorology Department, Poznań University of Life Sciences
ul. Piątkowska 94, 60-649 Poznań, Poland
e-mail: alinkadanie@gmail.com

INTRODUCTION

Studies devoted to the natural processes taking place in every plant have a rich historical background. The dependence of vegetation growth on environmental conditions and their common correlations are a crucial issue for researchers. The review of research by Law *et al. (*2002) presented such a correlation. It presented the dependence between temperature and precipitation with the annual ecosystem production, and also the relation between stomata transpiration (water released to the atmosphere) and CO_2 assimilation (carbon uptake from the atmosphere). They also found a correlation between the seasons of the year (with their individual characteristics) and the ability of an ecosystem to assimilate CO_2. The rate, intensity and quantity of processes listed above is determined by several environmental factors such as: light quality, temperature, water content (Barr *et al.* 2007) and also biochemical factors such as the length of growing season and light response. The type and age of tree stands, soil properties, forest management and site longitude also influenced the ecosystem release/assimilation of Greenhouse Gases (GHG) from the atmosphere. The rate of the carbon dioxide efflux from the soil is influenced by temperature jointly with soil moisture and can be expressed by the Q_{10} coefficient (Tjoelker *et al.* 2001, Pavelka *et al.* 2007). The Q_{10} coefficient is defined as the proportional change in carbon dioxide efflux resulting from 10°C increase in temperature. Temperature, as a soil influencing factor, is also related to the activity of micro-organisms. Together with water availability and organisms, it influences soil decomposition, nitrification and mineralization (carbon, nitrogen and nutrient cycle) (Hobbie *et al.* 2006). The plant reaction to increased CO_2 concentration was also examined by several researchers (Niinistö *et al.* 2004,

* The research is financed by the State Forest National Holding in Warsaw. We would like to thank the foresters from the Tuczno Forest District for allowing the use of pine forest stand and support during the measurements and field work. Sincere thanks to the Biomet lab, UBC, Vancouver, Canada, for all help with our EC system.

Janssens *et al.* 1998, Saxe *et al.* 1998). According to Valentini *et al.* 2000 the ecosystem respiration appears to go up just as latitude increases and quite the opposite occurs when the mean annual temperature decreases. Furthermore, the CO_2 efflux from soil is strongly correlated with temperature (Janssens *et al.* 2001). The wide variety of environmental factors and individual site conditions are related to both types of respiration: autotrophic and heterotrophic.

In recent years several techniques were applied for GHG exchange measurements in different ecosystems across Europe. As a standard method, the Eddy Covariance (EC) technique is applied for the measurement of mass and energy exchange between the land surface and the atmosphere. In the last 20 years the detailed description of wide variety of experiment with EC in different ecosystem have been published in the frame of such European project like CARBOEUROPE-IP, FLUXNET, EUROFLUX etc. (Valentini *et al.* 2003, Aubinet *et al.* 2000, Baldocchi *et al.* 2001). The scale of research ranged from molecular (single cell, leaf or needle) to ecosystem (single plant, forest stand) (Urban 2003).

The main goal of this paper is to present the primary results of EC measurements from the Tuczno forest site located in Poland for the year 2009. The estimation of CO_2 and H_2O fluxes exchange in the Scots Pine forest stand (afforestation) will be analysed under environmental and meteorological site condition. Moreover, we would like to determine the relationship between temperature, precipitation and radiation at the forest stand. The structural description of the Tuczno measuring site and the applied techniques will be presented further on.

MATERIAL AND METHODS

Site description

The study site is located in the Tuczno Forest District (North-West of Poland, 53º11'N, 16º5'E), about 40km west from Pila. The study canopy is composed of 52-year-old Scots pine (*Pinus sylvestris* L.) and birch (*Betula pendula* ROTH) trees, which cover 99% and 1% respectively. This species composition is typical for a vast part of Polish lowland forests, where about 60-year-old Scots pine afforestation is prevailing. The average tree diameter at the breast height (DBH) is 21cm and the average tree height is about 20 m. The average annual precipitation and air temperature observed at this site are 570 mm and 7.6ºC, respectively. These meteorological characteristics are similar to the average values measured in Poland in places where precipitation reaches 600mm and air temperature 8.5ºC. Western wind is most common in Tuczno, while southern and north-western winds are most typically observed in Poland. The growing season lasts approximately 220 days. The under-canopy vegetation consists mainly of beeches (*Fagus sylvatica* L.) and hornbeams (*Carpinus betulus* L.). The soil in this area is typical podzols according to the FAO classification.

Eddy Covariance and micrometeorological measurements

The Eddy Covariance (EC) technique is a standard method of ring gas and heat exchange over a wide range of ecosystem. The EC methodology is widely applied in European countries such as: Finland, France, Italy and others (Launiainen *et al.* 2005, Lund *et al.* 2007, Nakai *et al*. 2008, Ilvesniemi *et. al*. 2009). It is also commonly used in American and Asiatic countries: the USA, Canada, Japan and others (Baldocchi *et al.* 2003, 2005, Guan *et al.* 2006, McCaughey *et. al* 2006, Hirata *et al.* 2007, Misson *et al*. 2007, Kominami *et al.* 2008). Therefore, the EC technique is also applied at the Tuczno forest site.

The EC system is installed at a 4-meter tall mast, which is mounted on the top of 34-meter tower. The measuring system consists mainly of two instruments: an open path infra-red analyzer IRGA Li-7500 (Li-Cor, Lincoln, NE, USA) and a three dimensional asymmetric sonic anemometer CSAT3 (Campbell Scientific, Logan, UT, USA). Both instruments operate at a 20Hz sampling rate. Moreover, the Photosynthetic Photon Flux Density (PPFD) is measured by Quantum sensor (SKP 215) (Skye, UK). The basic meteorological parameters such as: wind speed and direction, precipitation (without snow), barometric pressure, air temperature and relative humidity are measured by an automatic weather transmitter WXT510 (Vaisala, Helsinki, Finland). The weather station has been operating since August 2009. All sensors are connected to a data-logger CR5000 (Campbell Scientific, Logan, UT, USA). The power supply system consists of two sets of 24DCV batteries. The obtained data are stored on a data-logger compact flash disk, which is connected to the local field computer. The applied system ensures proper data protection. The EC system has been continuously in operation since January 2008. The basic information related to the canopy structure is described by a hemispherical photography. The equipment used for this technique consists of a digital SLR camera Canon EOS 5D (12 MP matrix) with a Sigma EX fisheye lens – 8 mm, f/3.5. Gap Light Analyser is applied for the analysis of hemispherical photos (Chojnicki *et al.* 2009).

The Net Ecosystem Production (NEP) denotes the net production of organic carbon by plants (Kirschbaum *et al*. 2001). The NEP can be considered a result of subtracting the Ecosystem respiration (R_{ECO}) from the Gross Ecosystem Production (GEP) – Figure 1.

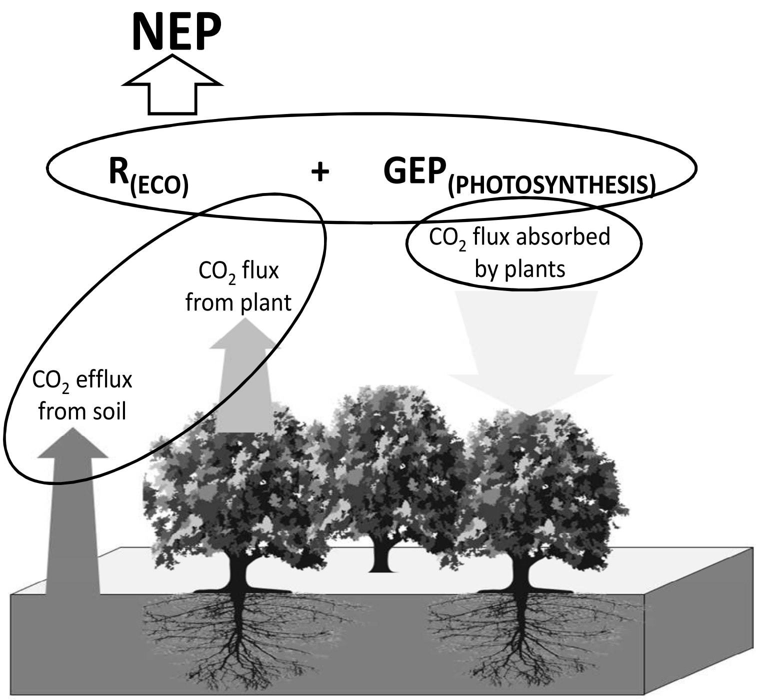


Fig. 1. The carbon cycle in the forest ecosystem

A positive value of the NEP indicates that CO_2 is gained by a forest ecosystem and a negative NEP value indicates that carbon dioxide is lost. Evapotranspiration is as a combination of physical and physiological evaporation, which is a result of plant gas exchange. In order to estimate the water cycle (including evapotranspiration) in a terrestrial ecosystem a large number of parameters and coefficients, which are necessary in numerical modelling, is required.

RESULTS FROM THE TUCZNO FOREST SITE RESEARCH

Meteorological Background

The meteorological data (daily average air temperature and precipitation totals) for the time period from August to December were obtained from the WXT510 Vaisala Meteorological Station. The station was installed on a mast, which was mounted on the top of the Tuczno measuring tower. For the year 2009 the meteorological data were obtained from the Pila meteorological station, which is located about 40 km west from the Tuczno site.

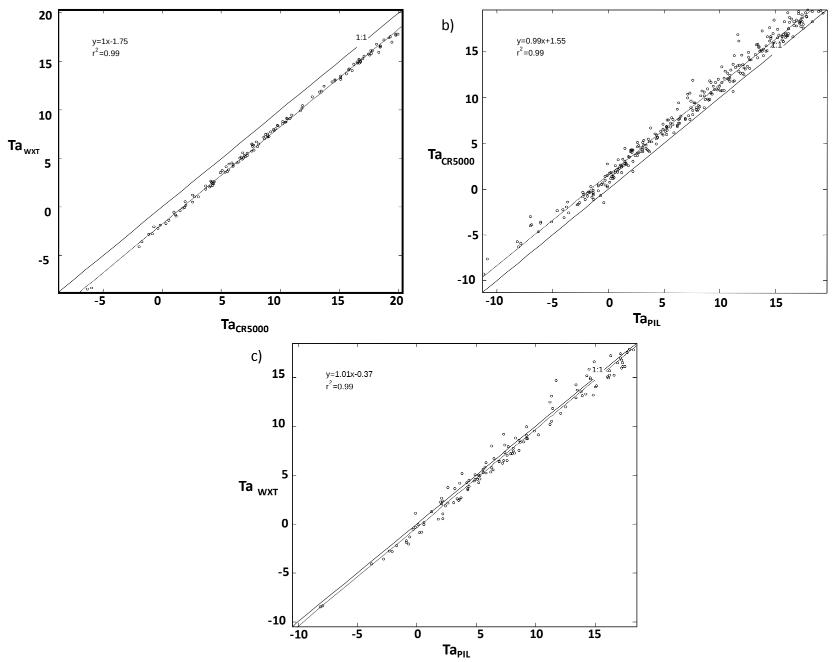


Fig. 2. The correlation between daily average air temperature recorded for the Tuczno forest site. Fig. a) Vaisala meteorological station vs. CR5000 data-logger at the Tuczno measuring tower
Fig. b) CR5000 data-logger vs. Pila meteorological station
Fig. c) Vaisala meteorological station vs. Pila meteorological station

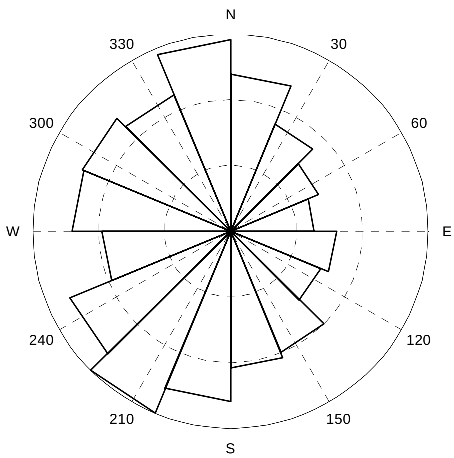


Fig. 3. Wind rose at the Tuczno forest site in the year 2009

The information about the daily average temperature recorded by the CR5000 data-logger panel (Ta_{CR5000}) from January 2008 was available. Taking into consideration the equipment location (installed on the top of the tower) the obtained data show a high correlation with the Pila (Ta_{PILA}) and Tuczno (Ta_{WXT}) daily average values of air temperature (Fig. 2b, Fig. 2a). Taking into account the relation between these meteorological parameters (Fig. 2c), the data from the Pila station for the first six months of 2009 were adopted for further analyses.

Throughout 2009 the mean annual air temperature was about 8.6°C and the precipitation was about 512 mm (Fig. 4a, Fig. 4b). In the analysed year the maximum air temperature occurred in late July (31.2°C) while the lowest value was observed in early January (–20.4°C). The mean annual precipitation was about 512 mm. The monthly precipitation reached the highest values of about 74 mm and 67 mm in October and May respectively. The lowest precipitation records of 2 mm and 18 mm were observed in April and January respectively. According to the applied EC methodology, the wind direction definition is extremely important for the future data calculation. In 2009 western wind was prevailing at the Tuczno forest site (Fig. 3).

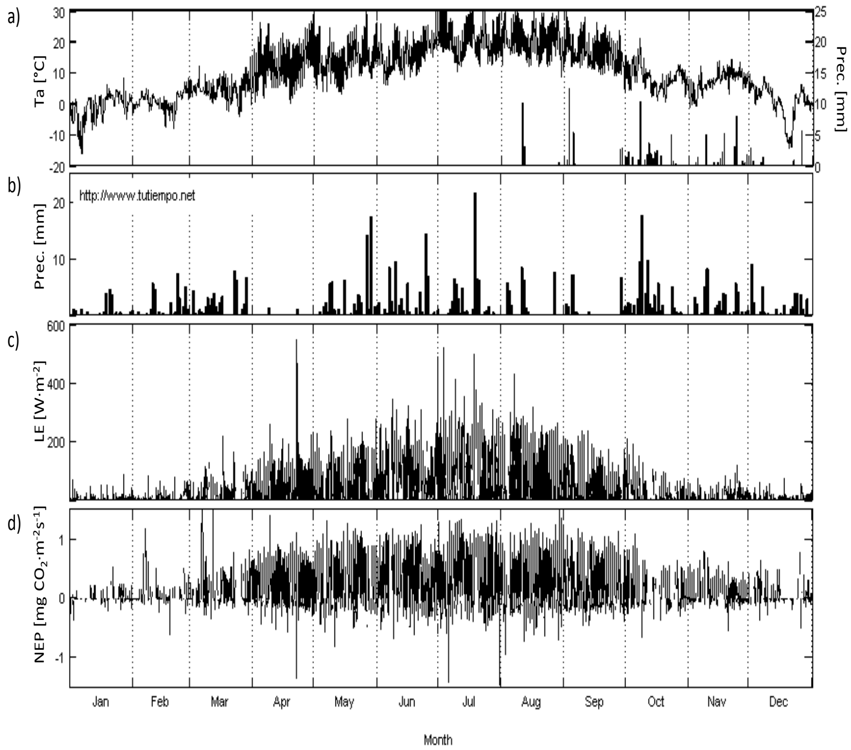


Fig. 4. The annual course of basic meteorological parameters from the Tuczno forest site for the year 2009

Fig. a). the annual course of air temperature and precipitation from WXT510 Vaisala meteorological station

Fig. b). the daily sum of precipitation from Pila meteorological station

Fig. c). the Tuczno forest daily water vapour fluxes (LE) course

Fig. d). the Tuczno forest daily Net Ecosystem Production (NEP) course in year 2009

Net Ecosystem Production (NEP) fluxes

Throughout 2009 the daily NEP values varied from –1.5 to 1.5 mg CO_2 m^{-2} s^{-1} (Fig. 4d). The negative NEP was observed from June to December, while the positive NEP values during the period from March to May. In the remaining months of the year the NEP values did not significantly differ from each other. The negative NEP values, which occurred during the vegetation season, could be the outcome of a decrease in the Photosynthetic Photon Flux Density. The reduction of radiation, which was partly absorbed by clouds, scaled down the light, which could reach the needle/shoots surface. The additional environmental factors, such as precipitation and temperature, were strongly NEP-related due to the increase in microbiological activity in the soil. The processes described above increase the CO_2 flux from forest stand (R_{ECO}). In October and November, when the average precipitation was about 5mm at the Tuczno site, the CO_2 uptake was significantly reduced and for a short period in 52 years the forest stand was a source of carbon dioxide. The annual precipitation in 2009 in the area of the Tuczno forest site was about 512 mm. The soil humidity, which strongly depended on precipitation, also influenced the GHG uptake/emission from the forest ecosystem. The high soil respiration, which stemmed from the increase in soil humidity and microorganism activity, significantly influenced the forest ecosystem capacity to release CO_2 into the atmosphere.

Water vapour (LE) fluxes

Throughout 2009 the daily values of water vapour fluxes (LE) varied from 0 to 580 W m^{-2} (Fig.4c.) and revealed a similar course to the NEP fluxes. In winter the LE fluxes dropped below 100 W m^{-2}. In contrast, in summer the average LE values were significantly higher (about 300-400 W m^{-2}). This phenomena were strongly correlated with the fluctuation of solar radiation intensity, which influenced the energy in ecosystem. Both, LE and NEP were related to the season of the year and the plant physiological development. In summer the NEP fluctuation was linked to the variability of the daily evapotranspiration fluxes. The intensive tree growth significantly sped up the production of CO_2, which was assimilated by plant cells in photosynthesis. Furthermore, the water transpiration was also higher in summer than in winter. The increase in H_2O fluxes, which was recorded from March to June, could be connected with the growing forest floor evaporation. The basic environmental parameters, such as the air temperature and precipitation, were the crucial elements, which influenced the hourly, daily and annually courses of carbon dioxide and water vapour fluxes.

GEP versus PPFD dependency

Gross Ecosystem Production (GEP) mainly depends on the Photosynthetic Photon Flux Density (PPFD) values, however such factors as air and soil temperature, precipitation, tree species and age cannot be disregarded due to the complexity of forest ecosystems (Black *et al.* 1996, Pilegaard *et al.* 2001, Carrara *et al.* 2003). Soil temperature, as one of the most important factors, influenced the intensity of plant physiological processes (photosynthesis or respiration). Moreover, it was strongly connected with the microorganism activity and was responsible for controlling the magnitude of soil CO_2 efflux. The correlation between such meteorological factors as precipitation, soil and air temperature influences the amount of water, which is absorbed by plants or is transpired into the atmosphere. Taking into consideration the above, it is highly complicated to describe the simple relation between the flux magnitude by parameter – PPFD or soil temperature. In the light of the previous statement, the model parametrization, which depends on the changes in ecosystems, is a key issue. The estimation of ecosystem respiration is as important as the quantification of the amount of net carbon dioxide gained by forest ecosystem (NEP). The gap filling procedure was based on a two-term function. The first term is a relation between PPFD and GEP, while the second term is an ecosystem respiration. In the literature several models of both, NEP (Falge *et al.* 2001, Carrara *et al.* 2004) and R_{ECO} (Barr *et al.* 2004, Lloyd and Taylor 1994, Fang and Moncrieff 2001) estimation were described. The "Nelder-Mead simplex direct search" algorithm (Lagarias *et al.* 1998) was selected for the models evaluation processes.

The data obtained from the Tuczno site were processed in terms of GEP versus PPFD dependency estimation. The Michealis-Menten (M-M) dynamic formula (1913), a model which is commonly used (equation 1), was applied to describe the relationship between these fluxes. The M-M formula coefficients were established for each month (Fig. 5). The relatively low determination coefficient values (r^2) for the December to February time period, were not a result of wrong selection of M-M model parameters. The application of different models, described in the literature, for such dispersive measuring points did not render satisfactory results. During winter months (beyond the vegetation season) the GEP fluxes were relatively low, which could be a major cause of low determination coefficient. Every change, which is present in the natural ecosystem, even the smallest one, strongly increases the observed values of GEP, measured by the EC system. Taking into consideration the limitation of applied measuring technique, which can be visible during the model evaluation and gap filling procedure, an additional measurement has to be incorporated into research (like chamber technique).

$$NEP = ((-\alpha \cdot PPFD)/(1-(PPFD/2000)+(\alpha \cdot PPFD/GEP_{opt})))+R_{day} \quad (1)$$

where: α – ecosystem quantum yield (µmol CO_2 m^{-2} s^{-1}),

PPFD – Photosynthetic Photon Flux Density (µmol m^{-2} s^{-1}),

GEP_{opt} – the optimum Gross Ecosystem Production (µmol m^{-2} s^{-1}) at an PPFD value of 2000 (µmol CO_2 m^{-2} s^{-1}),

R_{day} – the ecosystem respiration during the daytime (µmol CO_2 m^{-2} s^{-1}).

The CO_2 sequestration capacity of the Tuczno forest varied in 2009 with a PPFD equal to 500 µmol m^{-2} $s^{-1.}$ The average estimated GEP values in July, October and December were about 0.72, 0.89 and 0.33 µmol CO_2 m^{-2} s^{-1}, respectively. Also the optimum Gross Ecosystem Production (at PPFD value of 2000 µmol CO_2 m^{-2} s^{-1}) reached the highest values in summer (July GEP_{opt}= 23.87 µmol CO_2 m^{-2} s^{-1}), while the lowest in January (GEP_{opt}= 3.97 µmol CO_2 m^{-2} s^{-1}). The GEP versus PPFD interrelation described above was used for daily data gap filling procedures and the obtained data set was used for estimation of yearly total accumulated NEP.

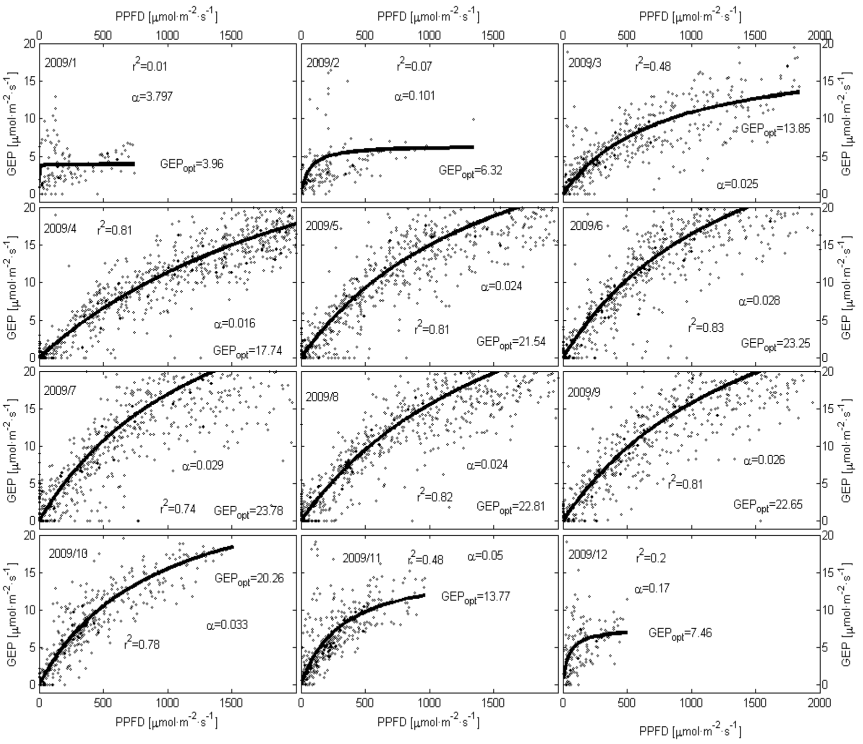


Fig. 5. Photosynthetic Photon Flux Density (PPFD) versus Gross Ecosystem Production (GEP) for the year 2009 at the Tuczno forest site

Air temperature (T_a) versus ecosystem respiration (R_{ECO})

At night, when there is hardly any radiation, plant activity is also significantly limited to respiration. For the night time gap filling procedure for the dependency between air temperature and ecosystem respiration was applied (Fig.6). The Schlentner and Van Cleve (1985) model (equation 2) was adopted for the calculation purposes (Fang and Moncrieff 2001).

$$R_{ECO,night}=(a/a+b^{(-(Tc-10)/10)})+c \qquad (2)$$

where: a,b,c – model parameters,

T_c – the air/soil temperature (°C).

The "Nelder-Mead simplex direct search" algorithm (Lagarias *et al.* 1998) was selected for the models evaluation processes. The obtained results show the high correlation between air temperature and respiration intensity. In winter, low temperature resulted in a reduced activity of soil microorganism and plant physiological processes. The ecosystem respiration rate, which is temperature-related, was also reduced to 2 μmol CO_2 m^{-2} s^{-1}. In warmer months the ecosystem activity increased significantly. Moreover, when the temperature ranged between 10 and 20°C, the ecosystem respiration consequently increased (R_{ECO} from 2-6 μmol CO_2 m^{-2} s^{-1}). Taking into consideration the GEP values (Fig. 5) a similar relation can be observed. The relation is especially visible in summer and autumn, where the highest values of R_{ECO} and GEP were recorded.

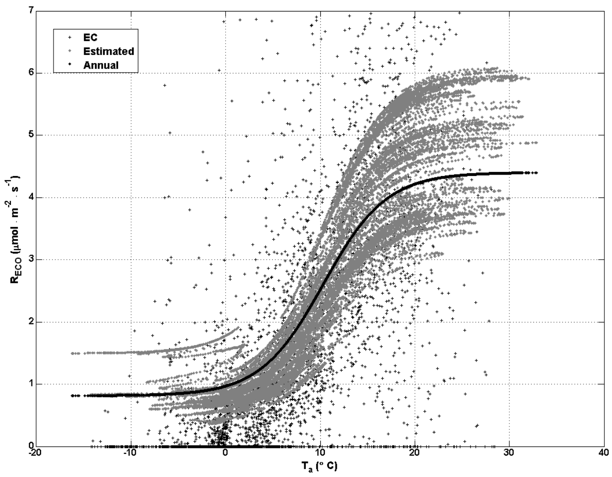


Fig. 6. The annual course of air temperature versus ecosystem respiration (R_{ECO}) for the year 2009 at the Tuczno forest site. The grey stars mark the eddy covariance measurement at the Tuczno site, black dots mark the result of Schlentner and Van Cleve (1985) model calculation, the grey crosses mark the average annual R_{ECO} course in 2009

DISCUSSION

Eddy Covariance technique

The EC technique, which is a standard method for the mass and energy exchange between an ecosystem and the atmosphere, is characterized by a high accuracy and a quality of obtained datasets. The modern, high frequency data collecting systems enable to make permanent and long-term observations. Within one measurement year the system allows collecting more than the 90% of the total data base, which is a highly satisfactory result. The gaps in the data, which are unavoidable, were related to different objective reasons, such as: lack of power supply, a storm, lack of turbulence in the air (especially at night) or a raindrop on the gas analyser measurement path. Moreover, the additional quality assurance (QA) and quality control (QC) check influence of the level of data applied for further calculation. The gaps, which were caused by the factors specified above, were filled in by the data from different numerical models (Michealis-Menten and Schlentner and Van Cleve). The application of these procedures allows the creation of coherent sets of data related to the mass and energy exchange between the Tuczno forest and the atmosphere.

CO_2 and H_2O fluxes

On the basis of EC measurement in 2009, the annual characteristics of CO_2 and H_2O fluxes were described. As the results from the Tuczno research site show, the daily course and magnitude of carbon dioxide and water vapour fluxes exchange between the forest ecosystem and the atmosphere were mainly related to following three factors:

- basic meteorological factors such as precipitation and air temperature,
- PPFD fluxes, which could be affected by the daily humidity course,
- plant development phase of the forest ecosystem and the soil temperature.

In early spring, the air temperature reached the values above $0^{o}C$. This temperature consequently affected the CO_2 fluxes, which ranged from 0 to 1.5 mg CO_2 m^{-2} s^{-1}. In comparison with the beginning of the year the days became longer and so the radiation reaching the soil surface went up (Fig. 4). These phenomena were observed in the fluctuation of the GEP values. In the Tuczno forest GEP values observed in February and March reached the values of about 0.17 and 0.61 $\mu mol \cdot m^{-2} \cdot s^{-1}$ respectively. In the second six months of 2009, it was observed that the CO_2 fluxes exchange between the forest stand and the atmosphere became more intense. This increase mainly stemmed from higher air temperature and plant development phase, which positively correlated with a surge in both photosynthesis and respiration. In August and September the highest GEP values were observed (about 1.0 μmol·m^{-2}·s^{-1}). The above values were undoubtedly linked to the highest PPFD records (about 2000 μmol·m^{-2}·s^{-1}). Similarly, the annual course of the second flux, water vapour, was also strongly correlated with the plant development phase and the amount of PPFD. It was clearly observed that almost every change in NEP values affected the LE records. This regularity resulted from the fact, that both analysed NEP and LE fluxes were influenced by the same plant physiological processes (photosynthesis versus respiration). It was noted that as the trees assimilated CO_2 more and more intensively, the transpiration to the atmosphere grew equally fast. In autumn and winter months the NEP/LE interdependence was established, but the lowest values were recorded.

CONCLUSIONS

1. The 52-year-old Scots Pine forest stand in Tuczno can be considered a strong sink of carbon dioxide since the total yearly uptake of this gas in 2009 was about 30 tonnes of CO_2 per hectare. The daily NEP and LE values in 2009 varied from –1.5 to 1.5 mg CO_2 m^{-2} s^{-1} and from 0 to 580 W m^{-2} respectively. Both, NEP and LE show a similar annual course in correlation with the meteorological parameters, PPFD and plant development phase.
2. On the basis of the data analyses, the intensity of the GHG (especially CO_2 and H_2O) exchange between the Tuczno forest ecosystem and the atmosphere was strongly connected with the air temperature and precipitation. In particular in winter, when the air temperature and precipitation decreased, the forest stand produced less CO_2, but still can be characterized as a carbon dioxide sink. Moreover, such parameters as the tree age, canopy structure, soil microorganism's activity etc. correlated with the amount of carbon dioxide and water uptake/absorption by the ecosystem. Furthermore, the net ecosystem production values were related to the PPFD fluctuation, which influences the plant photosynthesis intensity.
3. The presented dataset, which is a result of a one-year eddy covariance measurement in Poland, provides a proper basis for future development of the Tuczno forest site and can be compared with other, already published results of research covering longer time spans. Moreover, the presented data are important for evaluating the effect of global climate change on Polish forests and other possible influences on carbon and water cycles in forest ecosystems.

Acknowledgements

The authors would like express their gratitude to the State Forests National Holding (SFNH) for financial support of presented studies.

REFERENCES

Aubinet M., Grelle A., Ibrom A., Rannik U., Moncrieff J., Foken T., Kowalski A.S., Martin P.H., Berbigier P., Bernhofer Ch., Clement R., Elbers J., Granier., Grünwald T., Morgenstern K., Pilegaard K., Rebmann C., Snijders W., Valentini R., Vesala T., 2000. Estimates of annual net carbon and water exchange of forest: the EUROFLUX methodology. Advances in ecological research, 30, 113-173.

Baldocchi D.D., Falge E., Gu L., Olson R., Hollinger D., Running S., Anthoni P., Bernhofer Ch., Davis K., Evans R., Fuentes J., Goldstein A., Katul G., Law B., Lee X., Malhi Y., Meyers T., Munger W., Oechel W., Paw U, Pilegaard K., Schmid H.P., Valentini R., Verma S., Vesala T., Wilson K., Wofsy S., 2001. FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapour, and Energy Flux Densities. Bulletin of the American Meteorological Society, 11, 2415-2434.

Baldocchi D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biology, 9, 479-492.

Baldocchi D.D., Black T.A., Curtis P.S., Falge E., Fuentes J.D, Granier A., Gu L., Knohl A., Pilegaard K., Schmid H.P., Valentini R., Wilson K., Wofsy S., Xu L., Yamamoto S., 2005. Predicting the onset of net carbon uptake by deciduous forests with soil temperature and climate data: a synthesis of FLUXNET data. International Journal of Biometeorology 49, 377–387.

Barr A.G., Black T.A., Hogg E.H., Kljun N., Morgenstern K., Nesic Z., 2004. Inter-annual variability in the leaf area index of a boreal aspen-hazelnut forest in relation to net ecosystem production. Agricultural and Forest Meteorology, 126, 237-255.

Barr A.G., Black T.A., Hogg E.H., Griffis T.J., Morgenstern K., Kljun N., Theede A., Nesic Z., 2007. Climatic controls on the carbon and water balances of a boreal aspen forest. Global Change Biology 13, 561-576.

Black T.A., Den Hartog G., Neumann H.H., Blanken P.D., Yang P.C., Russell C., Nesic Z., Lee X., Chen S.G., Staebler R., Novak M.D., 1996. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest. Global Change Biology, 2, 219-229.

Carrara A., Kowalski A.S., Neirynck J., Janssens I.A., Curiel Yuste J., Ceulemans R., 2003. Net ecosystem CO_2 exchange of mixed forest in Belgium over 5 years. Agricultural and Forest Meteorology, 119, 209-227.

Carrara A., Janssens I.A., Yuste J.C., Ceulemans R., 2004. Seasonal changes in photosynthesis, respiration and NEE of a mixed temperate forest. Agricultural and Forest Meteorology, 126, 15-31.

Chojnicki B.H., Urbaniak M., Danielewska A., Strzeliński P., Olejnik J., 2009. Measurement of carbon dioxide exchange and biomass in forest ecosystem –measuring station in Tuczno (in Polish). Proceedings of the Centre for Nature and Forestry Education, 2 (21), 247-256.

Falge E., Baldocchi D.D., Olson R., Anthoni P., Aubinet M., Bernhofer Ch., Burba G., Ceulemans R., Clement R., Dolman H., Granier A., Gross P., Grünwald T., Hollinger D., Jensen N.O., Katul G., Keronen P., Kowalski A., Chun T.L., Law B.E., Meyers T., Moncrieff J., Moors E., Munger W.J., Pilegaard K., Rannik U., Rebmann C., Suyker A., Tenhunen J., Tu K., Verma S., Vesala T., Wilson K., Wofsy S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107, 43-69.

Fang C., Moncrieff J.B., 2001. The dependence of soil CO_2 efflux on temperature. Soil Biology & Biochemistry 33, 155-165.

Guan D.X., Wu J.B., Zhao X.S., Han S.J., Yu G.R., Sun X.M., Jin C.J., 2006. CO_2 fluxes over an old, temperate mixed forest in northeastern China. Agricultural and Forest Meteorology 137, 138-149.

Hirata R., Hirano T., Saigusa N., Fujinuma Y., Inukai K., Kitamori Y., Takahashi Y., Yamamoto S., 2007. Seasonal and interannual variations in carbon dioxide exchange of a temperate larch forest. Agricultural and Forest Meteorology 147, 110–124.

Hobbie S.E., Reich P.B., Oleksyn J., Ogdahl M., Zytkowiak R., Hale C., Karolewski P., 2006. Tree species effects on decomposition and forest floor dynamics in a common garden. Ecology, 87(9), 2288–2297.

Ilvesniemi H., Levula J., Ojansuu R., Kolari P., Kulmala L., Pumpanen J., Launiainen S., Vesala T., Nikinmaa E., 2009. Long-term measurements of the carbon balance of a boreal Scots pine dominated forest ecosystem. Boreal Environmental Research 14, 731-753.

Janssens I.A., Crookshanks M., Taylor G., Ceulemans R., 1998. Elevated atmospheric CO_2 increases fine root production, respiration, rhizosphere respiration and soil CO_2 efflux in Scots pine seedlings. Global Change Biology, 4, 871-878.

Janssens I.A., Kowalski A.S., Ceulemans R., 2001. Forest floor CO_2 fluxes estimated by eddy covariance and chamber-based model; Agricultural and Forest Meteorology, 106, 61-69.

Kirschbaum, M.U.F., Eamus, D., Gifford, R.M., Roxburgh, S.H., Sands, P.J., 2001. Definitions of some ecological terms commonly used in carbon accounting. In Net Ecosystem Exchange CRC Workshop Proceedings, Kirschbaum, M.U.F. & Mueller, R. (Eds), Cooperative Research Centre for Greenhouse Accounting, Canberra, Australia.

Kominami Y., Jomura M., Dannoura M., Goto Y., Tamai K., Miyama T., Kanazawa Y., Kaneko S., Okumura M., Misawa N., 2008. Biometric and eddy-covariance-based estimates of carbon balance for a warm-temperate mixed forest in Japan. Agricultural and Forest Meteorology 148, 723-737.

Lagarias J.C., Reeds J.A., Wright M.H., Wright P.E., 1998. Convergence Properties of the Neadler-Mead Simplex Algorithm in Low Dimensions. SIAM Journal of Optimalization, 9(1), 112-147.

Launiainen S., Rinne J., Pumpanen J., Kulmala L., Kolari P., Keronen P., Siivola E., Pohja T., Hari P., Vesala T., 2005. Eddy covariance measurements of CO_2 and sensible and latent heat fluxes during a full year in a boreal pine forest trunk-space. Boreal Environment Research 10, 569-588.

Law B.E., Falge E., Gu L., Baldocchi D.D., Bakwin P., Berbigier P., Davis K., Dolman A.J., Falk M., Fuentes J.D., Goldstein A., Granier A., Grelle A., Hollinger D., Janssens I.A., Jarvis P., Jensen N.O., Katul G., Mahli Y., Matteucci G., Meyers T., Monson R., Munger W., Oechel W., Olson R., Pilegaard K., Paw K.T., Thorgeirsson H., Valentini R., Verma S., Vesala T., Wilson K., Wofsy S., 2002. Environmental controls over carbon dioxide and water vapour exchange of terrestrial vegetation. Agricultural and Forest Meteorology, 113, 97-120.

Lloyd J., Taylor J.A., 1994. On the Temperature Dependence of Soil Respiration. Functional Ecology, 8, 315-323.

Lund M., Lindroth A., Christensen T.R., Ström L., 2007. Annual CO_2 balance of a temperate bog. Tellus 59B, 804-811.

McCaughey J.H., Pejam M.R., Arain M.A., Cameron D.A., 2006. Carbon dioxide and energy fluxes from a boreal mixedwood forest ecosystem in Ontario, Canada. Agricultural and Forest Meteorology 140, 79-96.

Misson L., Baldocchi D.D., Black T.A., Blanken P.D., Brunet Y., Curiel Yuste J., Dorsey J.R., Falk M., Granier A., Irvine M.R., Jarosz N., Lamaud E., Launiainen S., Law B.E., Longdoz B., Loustau D., McKay M., Paw K.T., Vesala T., Vickers D., Wilson K.B., Goldstein A.H., 2007. Partitioning forest carbon fluxes with overstory and understory eddy-covariance measurements: A synthesis based on FLUXNET data. Agricultural and Forest Meteorology 144, 14-31.

Nakai Y., Matsuura Y., Kajimoto T., Abaimov P., Yamamoto S., Zyryanova O.A., 2008. Eddy covariance CO_2 flux above a Gmelin larch forest on continuous permafrost in Central Siberia during a growing season. Theoretical and. Applied Climatology 93, 133-147.

Niinistö S.M., Silvola J., Kellomäki S., 2004. Soil CO_2 efflux in a boreal pine forest under atmospheric CO_2 enrichment and air warming. Global Change Biology, 10, 1363-1376.

Pavelka M., Acosta M., Marek V. M., Kutsch W., Janous D., 2007. Dependence of the Q_{10} values on the depth of the soil temperature measuring point. Plant Soil, 292, 171-179.

Pilegaard, K., Hunnelshøj P., Jensen N.O., Chen Z., 2001. Two years of continuous CO_2 eddy-flux measurements over a Danish beech forest. Agricultural and Forest Meteorology, 107, 29-41.

Saxe H., Ellsworth D.S., Heath J., 1998. Tree and forest functioning in an enriched CO_2 atmosphere. New Physiologist, 139, 395-436.

Tjoelker M., Oleksyn J., Reich P.B., 2001. Modelling respiration of vegetation: evidence for a general temperature-dependent Q_{10}. Global Change Biology, 7, 223-230.

Urban O., 2003. Physiological impacts of elevated CO_2 concentration ranging from molecular to whole plant responses. Photosynthetica, 41, 9-20.

Valentini R., Matteucci G., Dolman A.J., Schulze E.-D., Rebmann C., Moors E.J., Granier A., Gross P., Jensen N.O., Pilegaard K., Lindroth A., Grelle A., Bernhofer C., Grünwald T., Aubinet M., Ceulemans R., Kowalski A.S., Vesala T., Rannik Ü., Berbigier P., Loustau D., Gudmundsson J., Thorgeirsson H., Ibrom A., Morgenstern K., Clement R., Moncrieff J., Montagnani L., Minerbi S., Jarvis P., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861-865.

Valentini R., 2003. Fluxes of carbon, water and energy of European forests. Ecological studies. Springer, Berlin.

3. COMPARISON OF OBSERVED AND MODELED DAILY ECOSYSTEM RESPIRATION (R_{ECO}) AND NET ECOSYSTEM EXCHANGE (NEE)

Maria Michalak[1], Radosław Juszczak[1], Manuel Acosta[1], Bogdan H. Chojnicki[1], Jürgen Augustin[2], Matthias Drösler[3], Janusz Olejnik[1]

[1]Agrometeorology Department, University of Life Sciences in Poznań
ul. Piątkowska 94, 60-649 Poznań, Poland
[2] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, D-15374 Müncheberg, Germany
[3]Department of Ecology and Ecosystem Management, Technische Universitaet Muenchen, Am Hochanger 6, 85350 Freising, Germany
e-mail: mariamichalak@op.pl

INTRODUCTION

Wetlands in Poland occupy about 4 345 thousand ha, more than 80 percent of this area has been drained for the purpose of agriculture production and forest intensification, only 9 percent of peatlands preserved natural or close to natural status. Forests and shrub communities cover about 15% of total wetland area. The remaining area is occupied mainly by grasslands and, to a small extent by croplands (Mioduszewski 2004). Wetlands play a significant role in terrestrial carbon sequestration processes and they are considered as one of the biggest carbon pool on the Earth surface. It is estimated that approximately 455 Pg of carbon is stored in the northern hemisphere wetlands (Gorham 1991). Carbon dynamics in high-latitude wetland ecosystem is thought to respond dramatically to climate changes, such as temperature and precipitation changes that are predicted to occur under global warming conditions (IPCC 2001). Peatlands have historically been the net sink of carbon to upland systems, but their ability to store carbon in the future is uncertain. Warmer, drier weather could cause the water level to decrease dramatically and release much of the stored biomass carbon. The soils would become aerobic, giving microbes the oxygen, which will finally lead to the enhanced decomposition of the accumulated biomass.

It is generally considered that flooded soils are the sink of CO_2 (Conrad 1995, Scanlon and Moore 2000) However, in some condition soils would have to be considered as the net source of CO_2 (Guintas 2009). Peatlands, therefore, could be converted from a sink into a source of CO_2 (Brown 1998, Alm *et al*. 1999, Aurela *et al*. 2001).

The amount of carbon sequestered in a peatland in a specific year depends on the rate of plant production and the decomposition of organic matter in the ecosystem. Atmospheric CO_2 is bound by peatland vegetation through photosynthesis and is released in the process of respiration of plants and animals. Additionally, the CO_2 is emitted by soil microorganisms conducting the decomposition processes of soil organic matter. The total amount of CO_2 emitted from soil, plant and animals is called the Ecosystem Respiration (R_{eco}) (Alm *et al*. 1997). The assimilation of CO_2 is greatly influenced by high-frequency variation in solar radiation and by changes in the ground water table affecting the water content of mosses (Silvola and Aaltonen 1984). Ecosystem respiration is highly dependent on changes in temperature and soil moisture. The depth of the water table has an important effect on soil respiration. Davidson *et al*. (1998) have shown that water tables, because of their effect on O_2 supply to decompose microflora, provide the major control on CO_2 emission in soils with thick organic layers.

On the other hand, a spatial variation in carbon gas dynamics between peatland sites and even between plant communities within a site is considerable. Within a peatland site, one of the plant communities may act as a CO_2 sink while, simultaneously, another as a source (Waddington and Roulet 2000). Therefore, the ecosystem scale of CO_2 dynamics depends strongly on the plant communities composition and on the proportion of different communities in the ecosystem (Riutta *et al.* 2007). Moreover, an increased availability of nutrients, mainly N, may alter the carbon balance of peatlands. In nutrient-poor peatlands (bogs) the important peat forming *Sphagnum mosses* suffer essentially from competitive disadvantages if the N deposition gets too high (Lund *et al*. 2007).

Carbon dioxide fluxes can be quantified using different approaches. The applied techniques include micrometeorological methods such as eddy covariance (Aubinet *et al*. 2000, Baldocchi *et al*. 2000), aircraft measurements (Cihlar *et al*. 1992, Smitch *et al*. 2003) and direct measurements using various types of chambers (Livingston and Hutchinson 1995, Pumpanen *et al*. 2004). Chamber types include static, air-tight chambers and dynamic, flow-through chambers. The methods of measurements using closed chambers that follow the CO_2 mixing ratio changes in an isolated headspace above the surface are perhaps the most common techniques for quantifying peatlands CO_2 exchange (Livingston and Hutchinson 1995).

Our study was carried out at Rzecin wetland site (Olejnik *et al*. 2001, Chojnicki *et al*. 2007) administrated by the Department of Meteorology of the Poznan University of Life Sciences. It is the first wetland site-station in Poland where continuous measurements of greenhouse gases (CO_2, CH_4 and N_2O) exchange are carried out with the application of eddy covariance (CO_2 fluxes) and chamber techniques (CO_2, CH_4 fluxes).

The aims of this study were as follows: 1) to present reliable measurements of CO_2 fluxes measured at one summer day on the temperate bog ecosystem located in Poland using a closed dynamic chamber system, 2) to obtain the daily dynamics course of CO_2 fluxes over growing period.

MATERIALS AND METHODS

Site description

The study was carried out at Rzecin peatland site, Poland (52°45' N latitude, 16°18' E longitude, 54 m a.s.l.). The peatland covers the area of 140 ha. The vegetation is dominated by the following plant species: peat moss*: Sphagnum sp.*, *Dicranum sp.*; sedge grass*: Carex sp.*; reed: *Phragmittes communis;* bulrush: *Typha langifoli*; cranberry: *Vaccinium oxicoccu;*, common sundew*: Drosera rotundifolia*; common tormentil: *Potentilla palustri;*, buttercups: *Ranunculus acri,; bog-bean: Menyantes trifoliate* etc (Chojnicki *et al*. 2007, Wojterska *et al*. 2001). The peat substrate is a Limnic Hemic Floatic Ombric Rheic Histosol (Epidystric) according to FAO 2006 classification. In the middle of Rzecin wetland there is about 50 cm thick floating carpet peat-substrate overgrown mostly by mosses. The annual mean air temperature and precipitation for the whole period of measurements were 8.5°C and 526 mm, respectively.

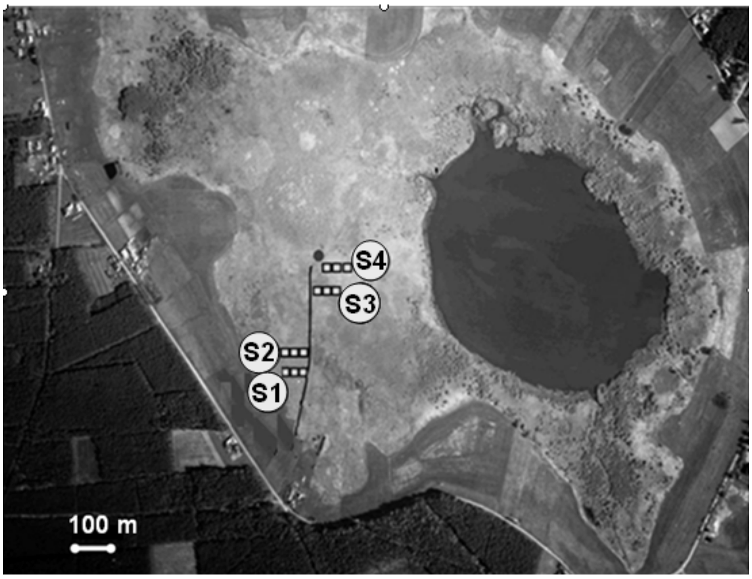


Photo. 1. The air photograph of Rzecin wetlands with the measurement site

CO_2 fluxes measurements

Four sites at Rzecin peatland were selected for the measurements of CO_2 fluxes. Each site consists of three plots and represents different vegetation type. The first site (S1) is dominated by *Caricetum elatae*, the second (S2) by *Calamagros-*

tietum neglectae, the third (S3) by *Menyantho-Sphagnetum teretis* and the fourth (S4) by *Sphagno apiculati-Caricetum rostratae* (Wojterska *et al*. 2001). The measurement sites are located along a 500-meter wooden path (Photo. 1). A PVC frame (75 x 75 x 20 cm) was inserted into the peat at the depth of about 17 cm at each plot. The frame was installed to provide better stability to the chamber and to locate plots where the measurements have to be made during the campaign period, i.e. to measure exactly the same place every time.

Chamber design

CO_2 fluxes measurements were carried out by means of a closed dynamic chamber system. The equipment consists of two chambers (dark and transparent), based on the model proposed by Drösler (2005). The chambers have a cubic shape (base 77 cm x 77 cm and height 50 cm) and the volume of 0.3 m^3. The dark chamber was made of white PVC (3 mm thick) in order to measure ecosystem respiration (R_{eco}) and reduce any influence of sun radiation. The transparent chamber was made of Plexiglas (3 mm thick), which allows light transmission of Photosynthetic Photon Flux Density (PPFD measured at µmol m^{-2} s^{-1}) up to 95% during the measurements of Net Ecosystem Exchange (NEE). Each chamber was equipped with two thermometers (T_107, Campbell Scientific, USA) in order to measure the air temperature inside and outside chamber during measurements. The temperature sensors were installed on the wall of the chamber, 35 cm above the bottom edge of the chamber and were protected against influence of light radiation.

Each chamber was equipped with two fans (Sunon, MagLev, Taiwan) with the flow of about 1 m s^{-1} to mix the air during measurement. The tightness of chambers during the measurement process was assured by installing a rubber gasket around the chamber lower edge and two elastic belts (outside of the chamber) connecting the top of a chamber and the base of the frame. To avoid problems with air temperature increase inside the chamber, a simple cooling system was applied. It consists of an ordinary touristic cooling packs placed inside the chamber on special frames, which exchange heat with the air blown by the fans (Drösler 2005).

The vertical profile of soil temperature at 2.5 and 10cm depth (T_109 Campbell Scientific) and PPFD (SKP215 Quantum Sensor, Skye Instruments Ltd, UK) were registered during the measurements. All sensors were connected to datalogger (CR 1000, Campbell Scientific, USA) which recorded values at 5-second intervals. Moreover, air temperature at the height of 2 m, a soil temperature profile at different depths (2, 4, 6, 10, 20, 30 and 50 cm) and PPFD were measured during the whole year at the site. Precipitation was measured automatically using a rain gauge (RG2-M, Onset, USA). No water stressed occurred at the wetland site during our measurement campaigns.

The results of measurements presented in this paper are related only to one summer campaign. Because sites S1 and S4 are 400 meter away from one another, it is impossible to measure all sites simultaneously. Thus, measurements were carried out on the 13^{th} and 14^{th} of May 2008 (sunny days without clouds). First day they were conducted at S1 and S2 sites and on the second day at S3 and S4. Measurements started early in the morning (before sunrise) and continued till late afternoon (about 6 pm). Each measurement conducted in dark and transparent chambers took from 3 to 5 minutes or 2 to 3 minutes, respectively. During the measurement period two basic principles were rigorously obeyed: 1) temperature inside the chamber should not change more than $1.5^{o}C$ and PPFD values should not change more than 10% from the beginning to the end of the individual measurement (Drösler 2005).

Data analysis

The CO_2 fluxes were calculated on the basis of the linear approach, considering the CO_2 concentration changes in the chamber headspace over time. The fluxes were calculated by means of Flessa et al., (1998) equation

$$F_{CO_2} = k_{CO_2} \cdot (273 \cdot T^{-1})\ (V \cdot A^{-1})\ (dc \cdot dt^{-1}) \tag{1}$$

where: F_{CO_2} – flux rate of CO_2 (mg CO_2-C m^{-2} h^{-1}), k_{CO_2} – gas-constant at 273.15 K (0.536 µg C μl^{-1}), T – instant air temperature during the measurement (K) at 2 m height, V – volume of the chamber (l), A – surface area within the collar of the chamber (m^2), $dc\ dt^{-1}$ – concentration change in the chamber atmosphere over time (CO_2: ml l^{-1} h^{-1})

The Gross Primary Production (*GPP*) is defined as the total amount of carbon fixed in the process of photosynthesis by plant in an ecosystem, while the Net Ecosystem Exchange (*NEE*) refers to GPP minus carbon losses (ecosystem respiration – R_{eco}). Ecosystem respiration (R_{eco}) is the result of plants, animals and soil respiration.

The R_{eco} and *NEE* were modeled between measurement campaigns with 30-minute intervals on the basis of the dependencies NEE vs. PPFD and R_{eco} vs soil temperature or air temperature. The R_{eco} was calculated on the basis of regressions between respiration rates and temperature using Lloyd & Taylor (1994) equation (2). E_o and R_{ref} of this equation were individually adopted to the corresponding dataset, whereas T_{ref} (283.15 K) and T_0 (227.13 K) were set as constant parameters (Lloyd & Taylor 1994):

$$R = R_{ref}\, e^{\,E_0\,(1/(T_{ref} - T_0) - 1/(T_{soil} - T_0))} \tag{2}$$

R – respiration (CO_2-C mg m^{-2} h^{-1}), R_{ref} – respiration at the reference Temperature (CO_2-C mg m^{-2} h^{-1}), E_o – activation energy (K), T_{ref} – reference temperature: 283.15 (K), T_0 – temperature constant for the start of biological processes: 227.13 (K), T_{soil} – soil temperature at the depth of best fit with the dataset (K).

The NEE was modeled based on the following equation (Whiting 1994; Bellisario *et al.*, 1998):

$$NEE = ((GP_{max}\ \alpha\ PPFD)((\alpha \cdot PAR) + GP_{max}))-1) - R \tag{3}$$

$PPFD$ – photon flux density of the photosynthetic active radiation (µmol m^{-2} s^{-1}), GP_{max} – maximum rate of carbon fixation at PAR infinite (CO_2-C mg m^{-2} h^{-1}), α = initial slope of the curve; light use efficiency (CO_2-C mg m^{-2} h^{-1}/µmol m^{-2} s^{-1}), R – respiration model (CO_2-C mg m^{-2} h^{-1}).

The statistical analyses were carried out by means of the Matlab numerical computing software (The MathWorks, USA) and the Table Curve 2D program (Curve Fitting Software, SYSTAT).

RESULTS AND DISCUSSION

Environmental conditions

The maximum daily values of Photosynthetic Photon Flux Density (PPFD) for both days of the measurement campaign reached about 1600 µmol m^{-2} s^{-1} at about 12:00 GMT and the courses of PPFD were similar (there were sunny days without clouds) (Fig. 1). Whereas, the daily courses of air temperature during these days were slightly different. The maximum temperature on the first day (13.05) was 19.5°C, whereas on the second day 21.0°C (Fig. 2). The overall ranges of air temperature during measurement campaign were from –2.0 to 21.0°C for 14.05.2008 and from 2.0 to 19.5°C for 13.05.2008. Wide ranges of measured PPFD values (from 0 to 1587 µmol m^{-2} s^{-1}) and air temperature created very good conditions to measure CO_2 fluxes (from the methodological point of view it gave us a wide range of measured fluxes).

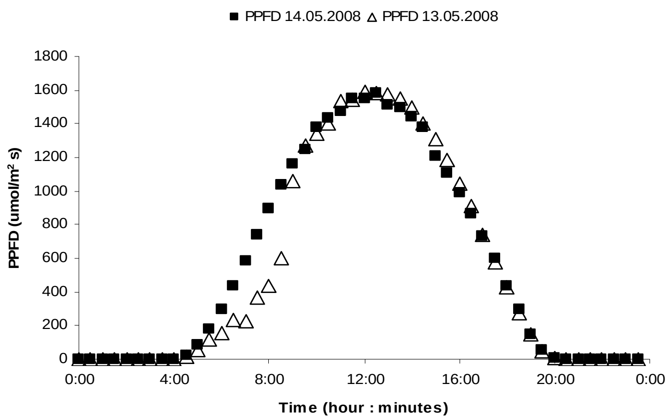


Fig. 1. The daily course of PPFD at Rzecin site on 13 and 14 of May 2008

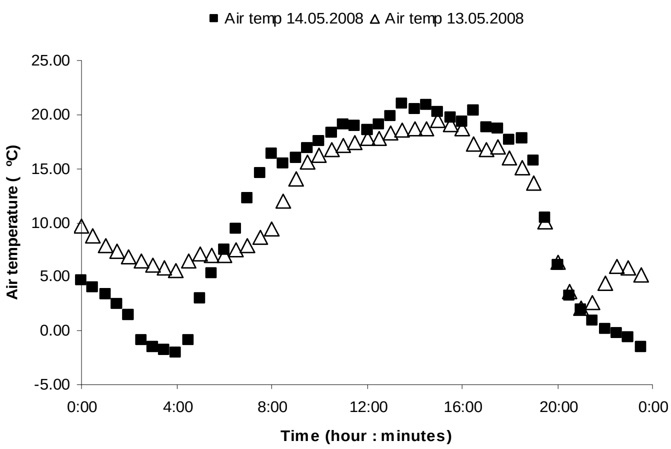


Fig. 2. The daily course of air temperature (2 m) at Rzecin site on 13 and 14 of May 2008

Analyses of dependencies of R_{eco} and air and soil temperatures indicated that the air temperature correlates better with R_{eco} than soil temperature (higher regression coefficient was found with air temperature). R_{eco} and air temperature showed a significant relationship in all four sites (mean regression coefficient was $r^2 = 0.75$). The highest correlation was found at S1 site (up to $r^2 = 0.90$) and the lowest at S1 site $r^2 = 0.66$.

Temperature is one of the most important factors controlling CO_2 fluxes (Amthor 1991). In the majority of studies, ecosystem respiration (R_{eco}) shows highly significant correlation with soil temperature (Lloyd and Taylor 1994, Buchman 2000). However, our results from this specific measurement campaign showed strong correlation of R_{eco} with air temperature. Similar relationship was found by Drösler (2005). In addition to temperature, water depth is another factor influencing CO_2 fluxes in wetland. The peatland surface area of Rzecin site consists of a floating carpet of a peat-substrate saturated with water, therefore, it can be assumed that during this campaign the peat substrate of all sites was saturated with water to the same extent and had similar influence on the measured fluxes. Consequently, the water depth impact on CO_2 fluxes was not assessed in this study.

CO_2 fluxes

The increase of CO_2 concentration was observed during the measurement of R_{eco} (dark chamber), (Fig. 3), while the decreasing trend of CO_2 concentration during the measurement of NEE (transparent chamber) (Fig. 4). During a single measurement (ca. 2 minutes) the decrease of CO_2 concentration reached even 50 ppm at the highest PPFD values. The coefficient of linear correlations between the changes of CO_2 concentration in the chamber headspace during measuring time ranged from 0.627 to 0.998, for both chambers. However, some fluctuations of CO_2 concentrations were observed during sampling period and it influenced the obtained linear correlation coefficients. However, it has no statistical significance for the calculated fluxes.

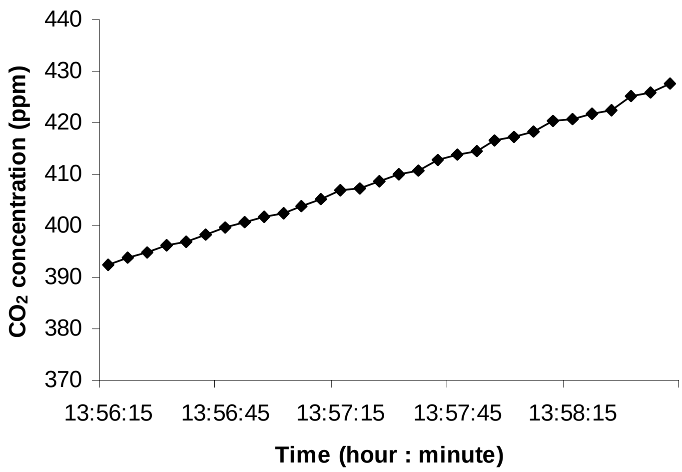


Fig. 3. CO_2 concentration run in dark chamber at site S2 on 13.05.2008.

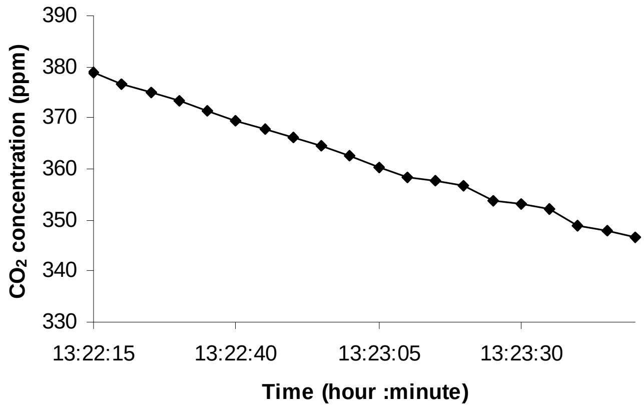


Fig. 4. CO_2 concentration run in transparent chamber at site S2 on 13.05.2008.

Daily courses of R_{eco} and NEE

R_{eco} rates during the measuring period ranged from 1.92 to 8.28 µmol CO_2 m^{-2} s^{-1} for all four sites. The rates of R_{eco} ranged from 2.44 to 6.08 µmol CO_2 m^{-2} s^{-1} for S1 site, from 2.00 to 5.35 µmol CO_2 m^{-2} s^{-1} for S2 site, from 1.92 to 5.36 µmol CO_2 m^{-2} s^{-1} for S3 site and from 2.07 to 8.28 µmol CO_2 m^{-2} s^{-1} for S4 site. The variations of R_{eco} values during the measuring campaign were related to changes in soil/air temperatures during the day. The highest rates of R_{eco} were observed during afternoon hours, which could be explained by the highest air temperature. S1 site dominated by *Caricetum elatae* and S4 site dominated by *Sphagno apiculati-Caricetum rostratae* showed the highest R_{eco}. Differences of R_{eco} among the sites were connected indirectly with a different vegetation composition (determined mostly by different ground water level and nutrient availability). In the contrary of our results, Heijmans *et al*. (2004) reported low values of R_{eco} in positions dominated by *Sphagnum*, in comparison to other plant species. He argued that this effect can be a result of lower soil temperature at positions dominated by *Sphagnum*. We consider that higher portion of R_{eco} at *Sphagnum* positions (S4 site) obtained in our measurements can depend on the depth of aeration zone which is slightly different at each site and requires more investigation in the future.

The daily courses of NEE were inversely proportional to the daily courses of PPFD, and NEE values ranged from 4.7 to –8.88 µmol CO_2 m^{-2} s^{-1}. NEE was significantly correlated, from the statistical point of view, with PPFD. The highest NEE was obtained usually at noon (approx. 11:00 to 13:00). We observed large variation of NEE at midday, but little variation in the early morning and late afternoon. NEE rates during the experiment period ranged from 4.7 to –5.58 µmol CO_2 m^{-2} s^{-1} at S1 site, from 2.59 to –8.88 µmol CO_2 m^{-2} s^{-1} at S2 site, from 1.87 to –6.79 µmol CO_2 m^{-2} s^{-1} at S3 site and from 3.34 to -7.24 µmol CO_2 m^{-2} s^{-1} at S4 site. The maximum values of NEE were observed at the highest values of PAR, a little bit earlier than maximum R_{eco} (which depends on temperature). All four sites showed similar diurnal patterns, but varied in magnitude. However, no significant differences of NEE between positions at the same site were found. The highest values of NEE were observed at S2 and S4 sites dominated by *Calamagrostietum neglectae* and *Sphagno apiculati-Caricetum rostratae* respectively and the lowers at the S1 site dominated by *Caricetum elatae*. We consider that differences of NEE among the sites are not only connected with vegetation composition, but also with air temperature and water depth, however a more detailed analysis is required in this respect.

At the beginning of the experiment period all positions had negative NEE values during the early morning measurements, as a result of balance between CO_2 assimilation and respiration, but at S1 and S2 positions it can also be the result of low quantity of photosynthetically active biomass, in comparison to the higher quantity of dead biomass. Therefore, these positions were dominated by R_{eco} rather than NEE, while PPFD values did not exceed 400 µmol m^{-2} s^{-1}. Thus, a wetland ecosystem can be either a net of CO_2 source or a net of CO_2 sink (eg. Hirota, 2006).

Modeled CO_2 fluxes: R_{eco} and NEE

The relationship between R_{eco} and air/soil temperature was calculated for individual sites by means of Lloyd and Taylor function (Fig. 5A). Then, on the basis of obtained *a* and *b* coefficients, R_{eco} was calculated (with 30 minutes steps) for the whole experimental period with the application of equation No. 2 and air/soil temperatures. In order to model NEE for the experimental period, the equation No. 3 was applied. In that case, the correlation coefficients obtained for rectangular hyperbola function were taken for modeling (Fig 5B).

In all cases, correlations between R_{eco} and temperatures, as well as between NEE and PPFD were statistically significant. The modeled curves differ from measured values on average 0.41 µmol m^{-2} s^{-1} for R_{eco} (mean absolute error (MAE) amount to 0.41) and 0.70 µmol m^{-2} s^{-1} for GPP (mean absolute error (MAE) amount to 0.70). The trends of modeled R_{eco} were very similar to the measured values in case of the sites S1-S3 (Fig. 6, Fig. 8, Fig. 10). The mean absolute error (MAE) for R_{eco} for sites S1, S2, S3, reached values 0.64, 0.67, 0.65, respectively. However, the MAE for site S4 was much higher indicating that the modeled values differ essentially from measured values (average MAE 2.4 µmol m^{-2} s^{-1}). The daily dynamics of modeled NEE values was very similar to the measured in case of sites S2 and S3 (Fig. 9 and Fig. 11). The MAE for sites S2 and S3 amount to 1.1 and 1.45, respectively. However, the modeled NEE for sites S1 and S4 were slightly underestimated in relation to the measured values (Fig. 7 and Fig.13). The MAE for these sites reached 1.96 and 2.22, respectively. This effect, however, will require deeper investigation in the future. Assuming that R_{eco} values are modeled correctly (the agreement between measured and modeled values is good), then it is most probable that the GPP values driven by PPFD are underestimated by model, or there are other drivers controlling the assimilation of CO_2 by plants within photosynthesis (eg. temperature?) not indicated by the model. If so, why does this effect not occur permanently for all sites? Table 1 shows the mean values of fluxes and mean standard deviations. The highest R_{eco} was estimated by model at S4 site (up to 3.31 g CO_2-C m^{-2} day^{-1}) and the lowest at S3 site (2.92 g CO_2-C m^{-2} day^{-1}).

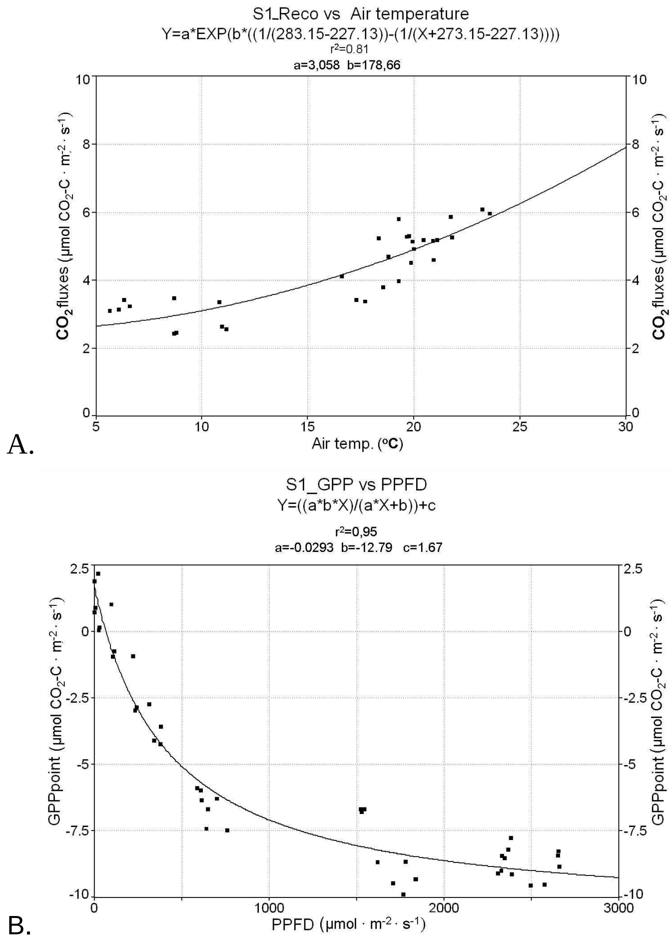


Fig. 5. R_{eco} versus air temperature at site S1 (A) and GPP versus PPFD at site S1 (B) on 13.05.2008.

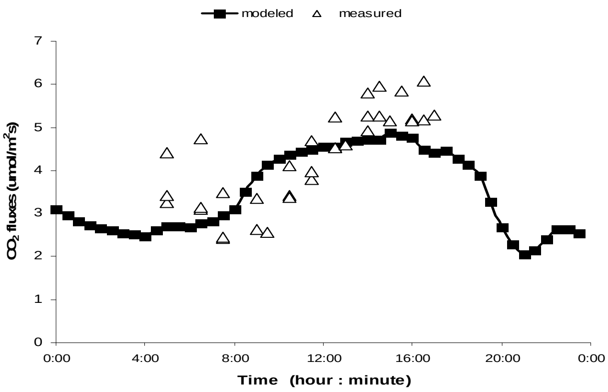


Fig. 6. Comparison of modeled and measured values of R_{eco} at site S1 on 13.05.2008

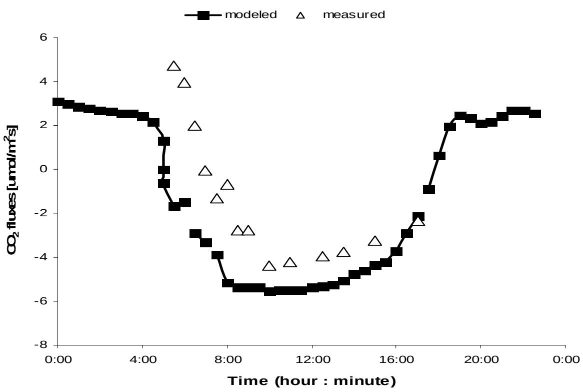


Fig. 7. Comparison of modeled and measured values of NEE at site S1 on 13.05.2008

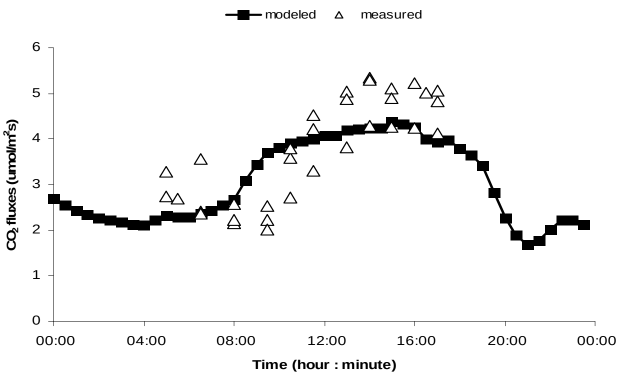


Fig. 8. Comparison of modeled and measured values of R_{eco} at site S2 on 13.05.

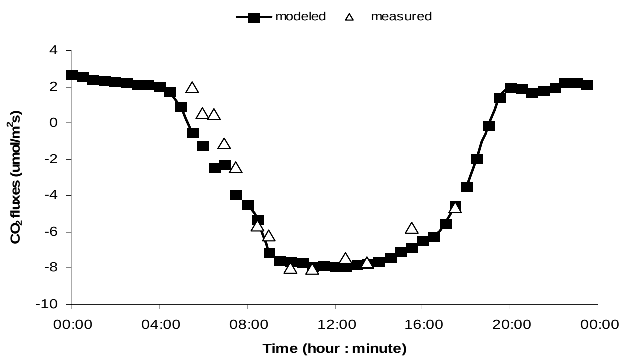


Fig. 9. Comparison of modeled and measured values of NEE at site S2 on 13.05.2008

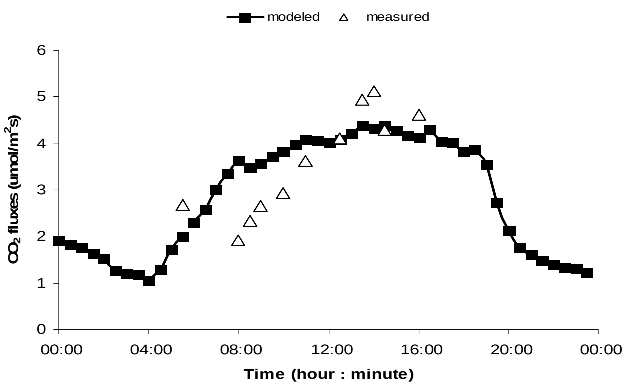


Fig. 10. Comparison of modeled and measured values of R_{eco} at site S3 on 14.05.2008

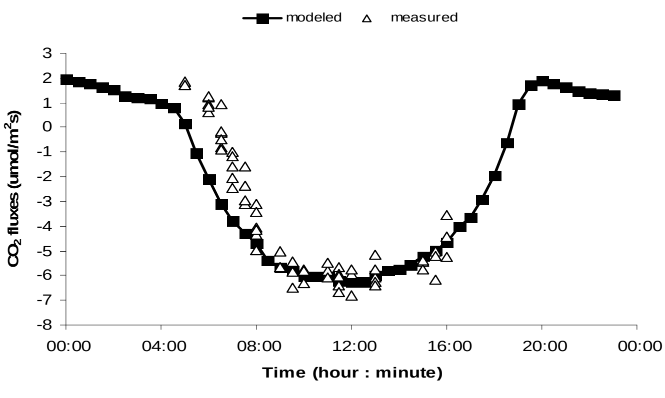


Fig. 11. Comparison of modeled and measured values of NEE at site S3 on 14.05.2008

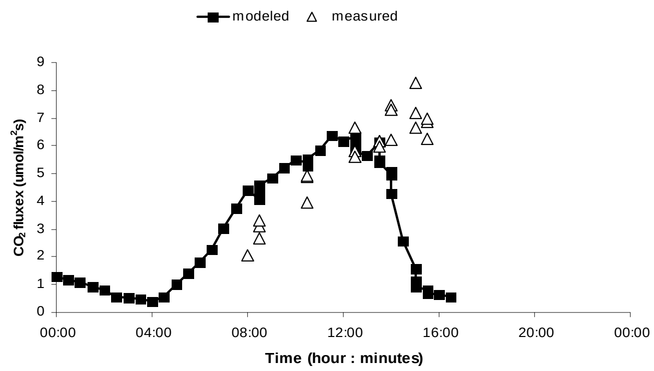


Fig. 12. Comparison of modeled and measured values of R_{eco} at site S4 on 14.05.2008

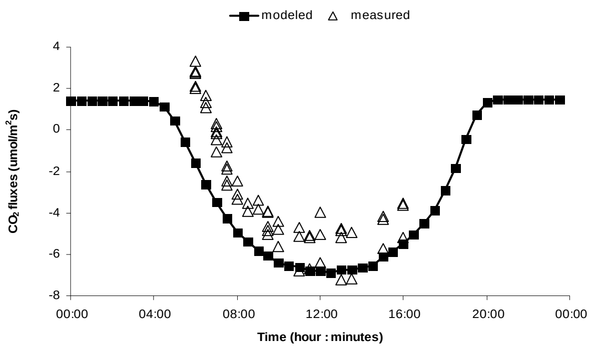


Fig. 13. Comparison of modeled and measured values of NEE at site S4 on 14.05.2008

Table 1. Mean values of fluxes modeled and measured

Site	R_{eco} (g m^{-2} day)	NEE (g m^{-2} day)
S1	3.63	–1.17
S2	3.12	–2.43
S3	2.92	–2.05
S4	3.31	–2.39

The modeled NEE values for the experimental day showed similar dynamics at all four sites. The highest cumulative NEE value was estimated at S2 (–2.43 g CO_2-C m^{-2} day^{-1}) and the lowest at S1 (–1.17 g CO_2-C m^{-2} day^{-1}). This can be related to different amount of aboveground biomass at each site and different photosynthetic activity of individual plant species. At S1 site, dominated by *Caricetum elatae*, there was still the highest amount of dead biomass (low assimilation), while at other sites there were more green parts. S2 and S4 sites showed very similar daily cumulative values of modeled NEE. (Tab. 2)

Table 2. Cumulative daily R_{eco} and NEE and standard deviations

Site	R_{eco} (μmol m^{-2} s^{-1})	Std	NEE (μmol m^{-2} s^{-1})	Std
	Avg		Avg	
S1	3.88	0.57	–1.70	1.42
S2	3.41	0.52	–3.46	0.75
S3	3.31	0.53	–2.81	0.61
S4	4.43	0.70	–2.57	1.12

Both, R_{eco} and NEE showed the temporal and spatial variation of CO_2 fluxes at our wetland ecosystem with similar trends/dynamics during the experimental days. Moreover, depending not only on vegetation composition, but also on environmental drivers (PPFD, temperature) and time of the day, our wetland ecosystem can switch from net sink to net source of CO_2 fluxes. This was also confirmed by other authors (Riera *et al*. 1999, Cole and Caraco 1998, Larmola *et al*. 2003, Hirota 2007). Nevertheless, it should be emphasized that the modeled R_{eco} and NEE were determined on the basis of short time research, and therefore, the obtained values should be carefully considered and regarded only as the estimation of fluxes. Future long term and in depth studies are necessary.

CONCLUSIONS

1. The results of our measurement showed the daily dynamics of CO_2 fluxes with respect to the time of measurements. Wide ranges of measured PPFD values and air temperature created very good conditions to measure CO_2 fluxes (from the methodological point of view it gave us wide range of measured fluxes). The daily courses of NEE were inversely proportional to the daily courses of PPFD. The highest values of NEE and R_{eco} during measurement campaign were observed at the sites dominated by *Sphagno apiculati-Caricetum rostratae* – this site revealed the highest exchange of CO_2.The highest values of R_{eco} and the lowest values of NEE at the site dominated by *Caricetum elatae* were the result of higher quantity of dead biomass. The variations of R_{eco} values during the measuring campaign were related to changes in soil/air temperatures during the day. However, vegetation composition, and water depth can also play an important role and have influ-

ence on measured CO_2 fluxes. This effect, not analyzed in this paper, requires more studies in the future.

2. The measured values of CO_2 fluxes revealed high coefficient of determination with Lloyd and Taylor function and rectangular hyperbola equation (Michaelis Menten), which were used to determine parameters necessary for modeling of R_{eco} and NEE. The values of mean standard deviation appear better fit to model of R_{eco} than NEE. However, the values of modeled R_{eco} and NEE showed positive correlation with measurement values. We proved that a chamber technique is a useful tool for determination of CO_2 fluxes at wetland or other ecosystems; it is simple to operate and relatively low as far as the cost and power consumption are concerned. As we measured ecosystem fluxes at a limited number of sites and during short time, it has to emphasized that only preliminary results of our study were presented in this paper.

Acknowledgements

The presented studies has been supported by the following European Community's Sixth Framework Programme projects: a GREENFLUX-TOK contract no. MTKD-CT-2006-042445 and CARBOEUROPE-IP contract no. GOCE-CT-2004-505572

REFERENCES

Alm J., Talanov A., Saarnio S., Silvola J., Ikkone E., Aaltonen H., Nykanen H., Martikainen PJ., 1997. Reconstruction of carbon balance for microsites in a boreal oligotrophic pine fen, Finland. Oecologia 110, 423-431. Alm J., Schulman L., Walden J., Nykanen H., Martikainen P.J., Silvola J., 1999. Carbon balance of a boreal bog during a year with an exceptionally dry summer. Ecology, 80, 161-74.

Amthor J.S., 1991. Respiration in a future, higher CO_2 world. Plant, Cell and Environment, 14, 13-20.

Aubinet M., Grelle A., Ibrom A., Rannik U., Moncrieff J., Foken T., Kowalski A.S., Martin P.H., Berbigier P., Bernhofer C., Clement R., Elbers J., Granier A., Grunwald T., Morgenstern K., Pilegaard K., Rebmann C., Snijders W., Valentini R., Vesala T., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Adv. Ecol. Res., 30, 113-175.

Aurela M., Laurila T., Tuovinen J.P., 2001. Seasonal CO_2 balances of a subarctic mire. J. Geophys. Res., 106, 1623-1637.

Baldocchi D., Finnigan J., Wilson K., Paw U.K.T., Falge E., 2000. On measuring net ecosystem carbon exchange over tall vegetation on complex terrain. Bound. Layer Meteorol. 96, 257-291.

Bellisario L.M., Moore T.R., Bubier J.L., 1998. Net ecosystem CO_2 exchange in a boreal peatland, northern Manitoba. Ecoscience, 5(4), 534-541.

Brown D.A., 1998. Gas production from an ombrotrophic bog – effect of climate change on microbial ecology. Climate Change, 40, 277-284.

Bubier J.L., Crill P.M., Moore T.R., Savage K., Varner R.K., 1998. Seasonal patterns and controls on net ecosystem CO_2 exchange in a boreal peatland complex. Global Biogeochem, Cycles 12, 703-714.

Buchman N., 2000. Biotic and abiotic factors controlling soil respiration rates in Picea abies stands. Soil Biology & Biochemistry, 32, 1625-1635.

Chojnicki B.H., Urbaniak M., Józefczyk D., Augustin J., Olejnik J., 2007. Measurements of gas and heat fluxes at Rzecin wetland. in: Wetlands: Monitoring, Modeling and Management. (eds) Okruszko *et al*., Taylor & Francis Group. London.

Cihlar J., Caramori P.H., Scnuepp P.H., Desjardins R.L., Macpherson J.I., 1992. Relation between satelite-derived vegetation indices ans aircraft-based CO_2 measurements. Journal of Geophysical Research, 97(17), 18,515-18,521.

Cole J.J., Caraco, N.F., 1998. Atmospheric exchange of carbon dioxide in a low- wind oligotrophic lake measured by addition of SF6. Limnology and Oceanography, 43, 647-656.

Conrad R., 1995. Soil microbial processes involved in production and consumption of atmospheric trace gases. Advances in Microbial Ecology, 14, 207-250.

Davidson E.A., Belk E., Boone R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Global Change Biology, 4, 217-227

Davidson E.A., Savage K., Verchot L.V., Navarro R., 2002. Minimizing artifacts and biases in chamber – based measurements of soil respiration. Agricultural and Forest Meteorology, 113, 21-37.

Drösler M., 2005. Trace gas exchange and climatic relevance of bog ecosystem, Southern Germany. PhD Dissertation, Lehrstuhl für Vegetationsokologie, Department für Ökologie, Technischen Universität München.

Flessa H., Wild U., Klemisch M., Pfadenhauer J., 1998. Nitrous oxide and methane fluxes from organic soils under agriculture. European Journal of Soil Science, 49, 327-335.

Gorham E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecological Applications, 1, 182-195.

Guintas M.E., Gil-Sotres F., Leiros M.C., Trasar-Cepeda C., 2009. CO_2 emission from soil under different uses and flooding conditions. Soil Biology & Biochemistry, 41, 2598-2601, 2009.

Heijmans M.M.P.D., Arp W.J., Stuart Chapin III F., 2004. Carbon dioxide and water vapour exchange from understory species in boreal forest. Agricultural and Forest Meteorolog, 123, 135-147.

Hirota M., Tang Y., Hu Q., Hirata S., Kato T., Mo W., Cao G., Mariko S., 2006. Carbon dioxide dynamics and controls in a deep-water wetlands on the Quinghai-Tibetan Plateau. Ecosystems, 9, 673-688.

Hirota M., Senga Y., Seike Y., Nohara S., Kunii H., 2007. Fluxes of carbon dioxide, methane and nitrous oxide In two contrastive fringing Jones of coastal lagoon, Lake Nakaumi, Japan, Chemosphere, 68, 597-603, 2007.

IPCC 2001. CLIMATE CHANGE 2001: Third Assessment Report of the IPCC. Cambridge University Press.

Larmola T., Alm J., Juutinen S., Saarnio S., Martikainen P.J., Silvola J., 2003. Flood can cause large interannual differences in littoral net ecosystem productivity. Limnology and Oceanography, 49, 1896-1906.

Law B.E., Falge E., Gu L., BaldocchI D.D., Bakwin P., Berbigier P., Davis K., Dolman A.J., Falk M., Fuentes J.D., Goldstein A., Granier A., Grelle A., Hollinger D., Janssens I.A., Jarvis P., Jensen N.O., Katul G., Mahli Y., Matteucci G., Meyers T., Monson R., Munger W., Oechel W., Olson R., Pilegaard K., Paw U K.T., Thorgeirsson H., Valentini R., Verma S., Vesala T., Wilson K., Wofsy S., 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agricultural and Forest Meteorology, 113, 97-120.

Livingston G.P., Hutchinson G.L., 1995. Enclosure-based measurements of trace gas exchange: applications and source of error. In Matson, PA., Harriss, RS., (Eds.). Biogenic Trace Gases: Measuring Emissions from Soil and Water. Blackwell Science, Cambridge, 14-50.

Lloyd J., Taylor J.A., 1994. On the temperature dependence of soil respiration. Functional Ecology, 8, 315-323.

Lund M., Lindroth A., Christensen TR., Strom L., 2007. Annual CO_2 balance of a temperate bog. Tellus, 59B, 804-811.

Mioduszewski W., 2003.Protection of water-related ecosystems and their role as water suppliers – Polish National Report. In: Convention on Protection and Use of Transboundary Watercourses and International Lakes. 13-14 December, Geneva, Switzerland.

Pumpanen J., Kolari P., IlvesniemI H., Minkkinen K., Vesala T., Niinistö S.,. Lohila A., Larmola T., Morero M., Pihlatie M., Janssens I., Yuste J. C.,. Grünzweig J. M., Reth S., Subke J., Savage K., Kutsch W., Østreng G., Ziegler W., Anthoni P., Lindroth A., Hari P., 2004. Comparison of different chamber techniques for measuring soil CO_2 efflux. Agricultural and Forest Meteorology 123, 159-176.

Riera J.L., Schindler J.E., Kratz T.K., 1999. Seasonal dynamic of carbon dioxide and methane in two clear - water lakes and two bog lakes in northern Wisconsin, USA. Canadian Journal of Fisheries and Aquatic Sciences, 56, 265-74.

Riutta T., Laine J., Aurela M., Rinne J., Vesala T., Laurila S., Haapanala S., Pihlatie M., Tuittila E.S., 2007. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem. Tellus, 59B, 838-852.

Scanlon D., Moore T., 2000. Carbon dioxide production from peatland soil profiles: the influence of temperature, oxic/anoxic conditions and substrate. Soil Science, 165, 153-160.

Silvola J, Aaltonen H., 1984. Water content and photosynthesis in the peat mosses Sphagnum fuscum and S. angustifolium. Ann Bot Fenn, 21, 1-6.

Smitch W., Kelly R.D., Wolker J.M., Fahnestock J.T., Reiners W.A., Hunt E.R., 2003. Leaf-to-aircraft measurements of net CO_2 exchange in a sagebrush steppe ecosystem. Journal of Geophysical Research, vol. 108, No. D3, 4122, doi:10.1029/2002JD002512.

Swanson R.V., Flanagan L.B., 2001.Environmental regulation of carbon dioxide exchange at the forest floor in the boreal black spruce ecosystem. Agricultural and Forest Meteorology, 108, 165-181.

Waddington J.M., Roulet N.T., 2000.Carbon balance of a boreal patterned peatland. Global Change Biol., 6, 87-97,

Whiting G.J., 1994. CO_2 exchange in the Hudson Bay lowlands: Community characteristics and multispectral reflectance properties. J. Geophys. Res., 99, 1519-1528.

Wojterska M., 2001. Szata roślinna Wielkopolski i Pojezierza Południowopomorskiego: Przewodnik sesji terenowych 52. Zjazdu Polskiego Towarzystwa Botanicznego, 24-28 września 2001.

4. MEASUREMENTS OF VERTICAL CARBON DIOXIDE NET FLUX IN THE CENTER OF ŁÓDŹ – PRELIMINARY RESULTS FROM THE PERIOD 2006-2009*

Włodzimierz Pawlak, Krzysztof Fortuniak, Mariusz Siedlecki

Katedra Meteorologii i Klimatologii, Uniwersytet Łódzki
ul. Narutowicza 88, 90-139 Łódź
email: wpawlak@uni.lodz.pl

INTRODUCTION

Carbon dioxide, although occupying very small part in atmospheric air, plays very important role in energy exchange system within the geographical environment. It participates in photosynthesis processes, which produces biomass increment, it is also a greenhouse gas, which impact on air temperature increase on Earth is widely discussed at the present time. Emission of this gas should be monitored, but from papers published so far it is evident that the intensity of CO_2 emission between surface and atmosphere is strictly connected with degree of anthropogenic modification of surface. Availability of sensors enabling the application of modern measurement techniques, like eddy covariance method, causes that measurements of turbulent carbon dioxide flux are carried out in many countries (Lee *et al*. 1996, Moncrieff *et al*. 1997, Baldocchi *et al*. 2000, Schmid *et al.* 2000, Grimmond *et al*. 2002, Coutts *et al*. 2007). Unfortunately, there are still not many on urban terrain, where carbon dioxide circulation is completely different in comparison with areas covered by plants, both natural and agricultural (Nemitz *et al*. 2002, Moriwaki and Kanda 2004, Vellasco *et al*. 2005, Vogt *et al*. 2006, Pataki *et al*. 2009).

The aim of this work is presentation of preliminary results of vertical turbulent carbon dioxide net flux measurements carried out in Łódź in the period July 2006-July 2009. The first measurements of energy balance components and CO_2 flux were carried out in Łódź in the period 2000-2004 (Offerle *et al*. 2003, Offerle *et al*. 2005, Offerle *et al*. 2006a, Offerle *et al*. 2006b, Fortuniak 2009) at the dense built-up city center and at post-industrial and residential areas, but these experiments were short timed lasted in one case a few months, but mostly the time coverage was restricted to few days. Such experiments couldn't answer the questions concerning characteristics of seasonal or annual variability of carbon dioxide net flux above

*Funding for this research was provided by a Polish Ministry of Science and Higher Education (State Committee for Scientific Research) under grant N N306 276935 in years 2008-2011.

urban terrain. Measurement described in this paper started in July 2006 and they are still being carried out. Presented data set is probably the first longtime (three years) data series of CO_2 flux registered in Poland above the urban terrain.

MEASUREMENT SITE DESCRIPTION

Measurement site is located at the west part of Łódź center (Fig. 1, right). Surroundings of measurement point, as it shows Figure 3, can be characterized by dense building development. Artificial surfaces (streets, buildings, pavements, parking lots, etc.) cover ~50-70% and approximately 30% are roofs of buildings (Kłysik 1998). Surfaces with vegetation (trees and lawn interspersed with buildings) cover about 40% of the area but trees which are mostly deciduous cover only 10% (Kłysik, 1998). Trees are deciduous, 8-15 m tall high but mainly below building height. There are also two green parks in the neighborhood of measurement site (Fig. 3) which are situated ~900 m on the south (Park Poniatowskiego) and approximately 1700 m on the west (Park "Zdrowie").

METHOD, INSTRUMENTATION AND DATA PROCESSING

Measurement system is installed at the 20 m tower mounted on the roof of 17 m tall building at Lipowa 81 Street (Fig. 1, left). Height of this building is similar to surrounded building development, which confirm the values of roughness length determined for close to the neutral stratification from the logarithmic equa-

Fig. 1. Measurement tower at Lipowa Street (left) and location of measurement point in Łódź (right)

tion of wind (Grimmond *et al*. 1998). Mean z_{0m} equals 2.5 m. Figure 2 (observations of z_{0m} by wind direction) shows the increase of z_{0m} to the west where new residential block of flats, exceeded the height of other building by ~10 m, was built. Mean height of surrounding buildings was estimated at 10.6 m, so measurement height 37 m above the ground layer is probably close to roughness sublayer (Grimmond and Oke 1999).

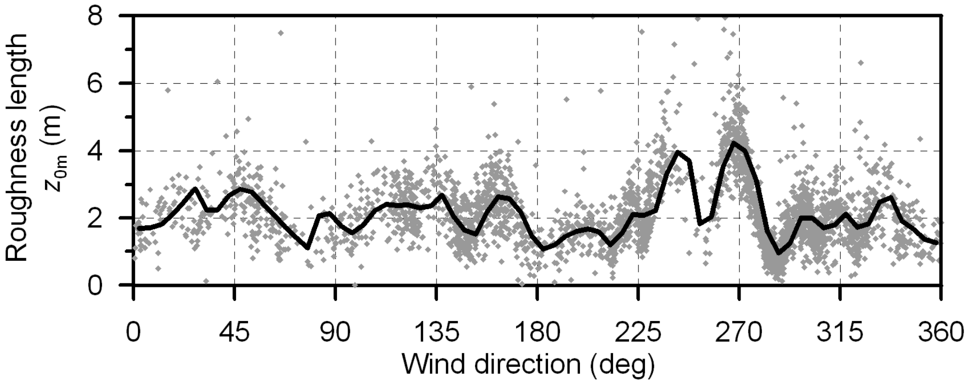


Fig. 2. Roughness length for momentum z_{0m} by wind direction (grey dots). Black line indicates 10 degrees mean of z_{0m}

Aerial photo at the Figure 3 shows the net of streets in the surroundings of the measurement point. High elevation of sensors results in large source area. Total source areas at level P = 90%, 75% and 50% evaluated for the analyzed period, for hours 10-14 during unstable conditions (all good data) with the aid of FSAM model (Schmid, 1994) surround measurement point with the circles with diameter up to 1 km. For neutral and stable conditions a source areas are probably larger and cover parks placed on the west and south. Source area of radiation sensors is much smaller and can be evaluated as a circle with approximately 250 m diameter (for P = 90%).

Eddy-covariance measurement set is mounted 1 m below top of the tower on its east side, approximately 1 m from the tower axis. Tower diameter is rather small (~0.15 m) so its influence on the turbulence can be neglected. Fluctuations of carbon dioxide ρCO_2' are measured with Li 7500 H_2O/CO_2 Infra Red Gas Analyzer (Li-cor, USA). Fluctuations of horizontal and vertical wind speed components *u*', *v*', *w*' and air temperature *T*' are measured with sonic anemometer RMYoung 81000 (RMYoung, USA). Both sensors are connected to 21X datalogger (Campbell Scientific, USA). These sensors, according to eddy covariance theoretical background, register data with high frequency (in this case 10 Hz) and store in 15 minutes block of data. Shortwave and longwave components of ingoing and

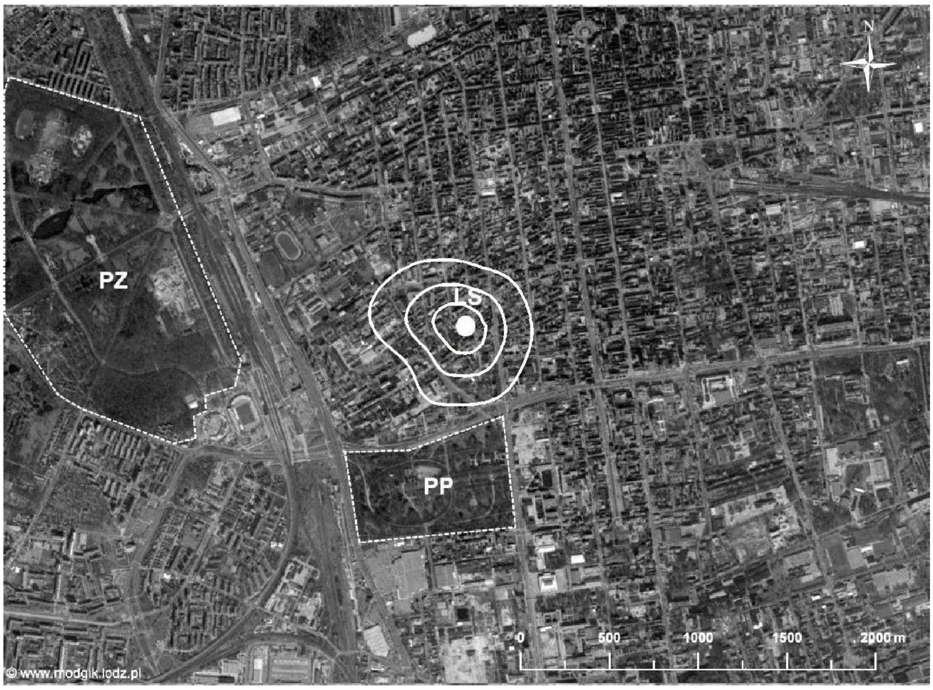


Fig. 3. West part of Łódź city center with location of measurement point (LS – Lipowa station) and urban parks located in nearest neighbourhood (PZ – city park “Zdrowie”, PP – city park “Poniatowskiego”). Solid lines surrounding measurement point indicate source areas at *P* = 50%, 75% and 90% calculated for turbulent fluxes measured at 10-14 at Lipowa Station for unstable stratification (all available data in the period July 2006 – July 2009)
Aerial photo source: Municipal Center of Geodesics and Cartographic Documentation of Łódź

outgoing radiation are measured every 1 minute by CNR1 net radiometer (Kipp&Zonen, Holland). Next, radiation balance *Q** is calculated as an algebraic sum of measured components. Moreover, basic meteorological parameters like air temperature and humidity, atmospheric pressure, wind speed and direction are registered every 10 minutes with additional sensors. Turbulent carbon dioxide net flux FCO_2 is calculated as a covariance of vertical wind speed fluctuation *w*’ and carbon dioxide density fluctuation *ρCO2*’:

$$FCO_2 = \overline{w'\rho CO_2'} \qquad (1)$$

Before flux calculation adequate procedures of data pre-processing are applied, which allows the elimination of errors from the data. First of all, data registered during rainfall or atmospheric deposits and when friction velocity u* was lower than 0.1 were removed. As a next step, maximization of covariance between *w*' and *ρCO2*' during the time interval +/– 2 seconds is carried out, which allows minimizing of the influence of the spatial separations of sensors. Spike detection procedure (Vickers and Mahrt 1997) is used to eliminate unrealistic values of data. Because the air flow above the urban terrain is not normally parallel to the surface and sonic anemometer, which causes non-zero values of mean vertical wind speed (0.1 of mean *w'* and ~1.5 deg of rotation angle corresponds to 0.1 ms-1 of mean vertical wind speed), double system coordinates rotation is added (Kaimal and Finnigan 1994, Finnigan 2004).Third rotation was omitted because of possibility of unrealistic results. After these procedures FCO_2 data is combined with radiation data. Moreover, adequate corrections are added, like sensible heat flux correction for sonic anemometer temperature (Schotanus *et al*. 1983) and WPL corrections for non-zero mean vertical wind speed caused by air density fluctuations (Web *et al*. 1980, Lee *et al*. 2004). The last step is the selection of data averaging period. Because of 15 minutes averaging period could be too short and spectral losses for low frequency are possible. In this case 30 minutes averaging period is used to calculate carbon dioxide net flux. Positive value of FCO_2 indicates upward vertical turbulent transport of carbon dioxide (emission from surface to the atmosphere) and negative FCO_2 indicates vertical transport to the surface, that is absorption of CO_2.

RESULTS

Figure 4 shows all correct values of radiation balance Q^*, carbon dioxide density ρCO_2 and turbulent vertical net flux FCO_2 registered in the center of Łódź in the period July 2006-July 2009. There is a clearly visible significant prevalence of positive over negative values of carbon dioxide net flux, which means that center of Łódź in the surroundings of measurement point was a source of carbon dioxide during whole analyzed period. Another feature which should be emphasize is an annual course of FCO_2 with maximum in wintertime and minimum in summertime. Maximum turbulent transport of CO_2, which in some cases reached ~70 μmol m^{-2} s^{-1} in cold season is related to strong emission of anthropogenic carbon dioxide which is an effect of fossil fuel combustion during houses heating and public transport (Kłysik 1996, Offerle *et al*. 2005). Summertime minimum with values mainly doesn't exceeded 15 μmol m^{-2} s^{-1} can be explained by decrease of anthropogenic CO_2 emission (no house heating, less intensive car traffic because of holidays) and absorption of CO_2 by plants.

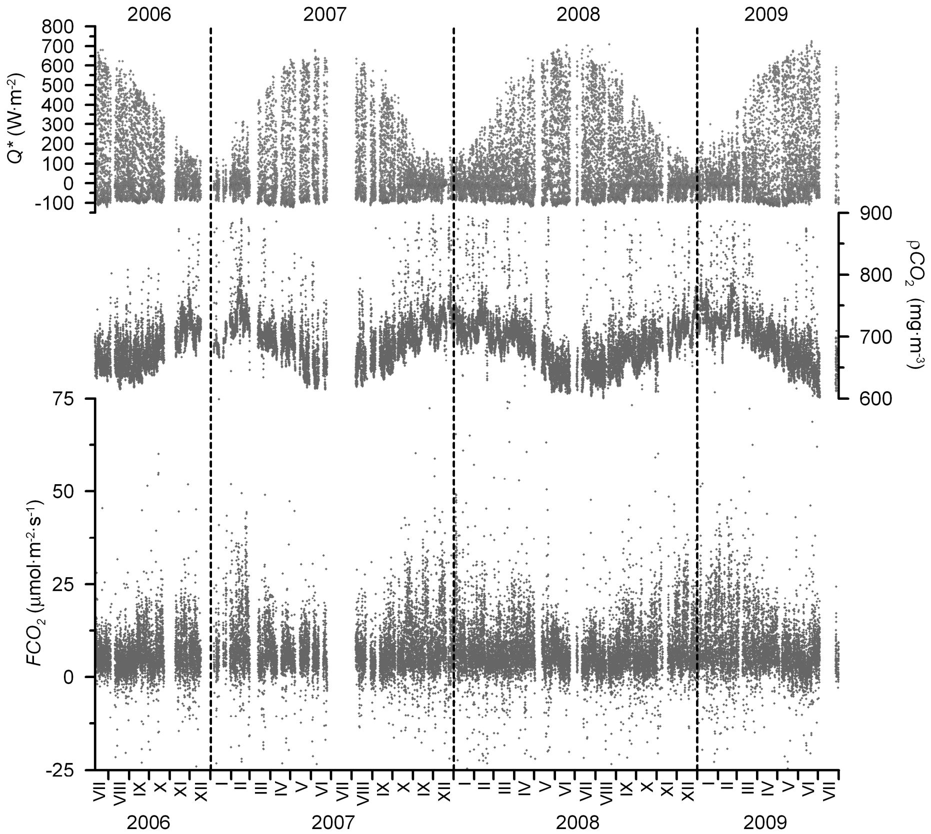


Fig. 4. 30-minutes means of radiation balance Q^*, carbon dioxide density ρCO_2, and turbulent flux FCO_2 recorded in the center of Łódź in the period July 2006-July 2009

As a next step, two simple procedures of data gaps filling were applied. The first procedure which assumed obtaining missing data through interpolation, was used in case of small gaps which did not exceed 3 hours. Longer gaps were filled by the data from mean diurnal pattern of FCO_2 calculated for adequate month. Mean amount of missing data doesn't exceed 20%. On the basis of obtained data, approximate monthly turbulent net fluxes of carbon dioxide were calculated. Because of many factors determines carbon dioxide turbulent exchange above urban terrain, precise calculation of monthly FCO_2 is very difficult and exceeds framework of this paper. Figure 5 shows the results of those calculations in comparison with the variability of mean monthly air temperature in the analysis period. There is a clear but not so strong negative correlation between mean monthly air temperature and intensity of carbon dioxide turbulent exchange in the centre of Łódź., which is confirmed by the determination coefficient $R^2 = 0.73$. Monthly net flux values were also a basis to obtain turbulent exchange of carbon dioxide during all year long. It can be estimated at ~10.2 kg m^{-2} $year^{-1}$ in 2007 and ~9.9 kg m^{-2} $year^{-1}$ in 2008. It means that analyzed part of Łódź city center is a significant source of CO_2 for the lower troposphere.

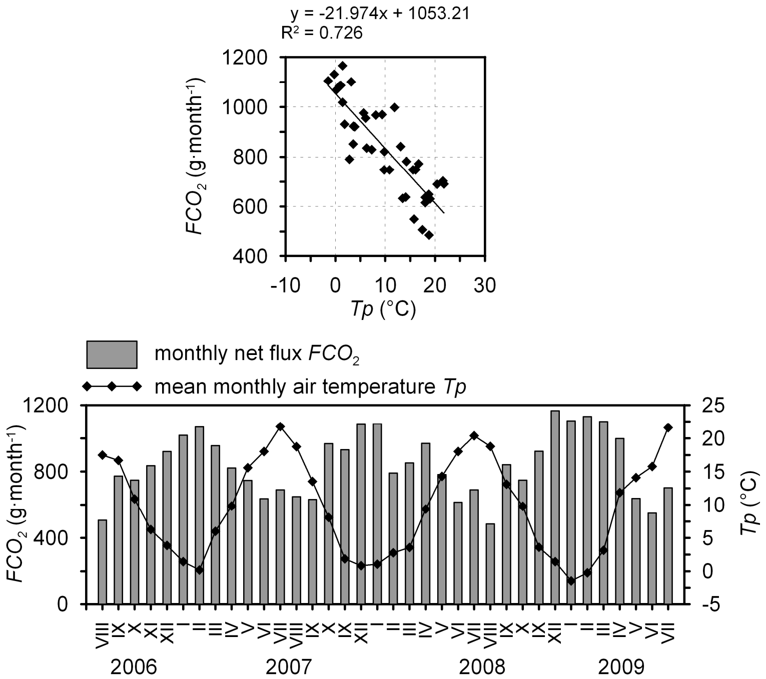


Fig. 5. Mean monthly net CO_2 exchange and mean monthly air temperature (down) and linear fit between mean monthly air temperature and mean monthly net CO_2 exchange (up) in the period July 2006-July 2009

Mean diurnal courses of carbon dioxide net flux calculated for months (Fig. 6) confirm annual pattern of its variability. What is particularly important, independently from time of the day and season, mean FCO_2 flux is always positive, which indicates the prevalence of carbon dioxide emission over absorption above analyzed part of the center of Łódź in the period July 2006-July 2009. Minimum intensity of CO_2 exchange, of the order of ~2 μmol m^{-2} s^{-1} is observed always during nigh time mainly because of weak turbulence. After sunrise FCO_2 increases because of, firstly, turbulent transport of carbon dioxide cumulated within the urban canyons during night, and secondly due to an increase of anthropogenic CO_2 emitted by public transport. This phenomenon is clearly observed during cold season, when FCO_2 reaches values higher than 12 μmol m^{-2} s^{-1} and variability of CO_2 density is determined only by anthropogenic sources and biological processes are insignificant. Mean FCO_2 reaches maximum value always during the day, which is also connected with public transport intensity.

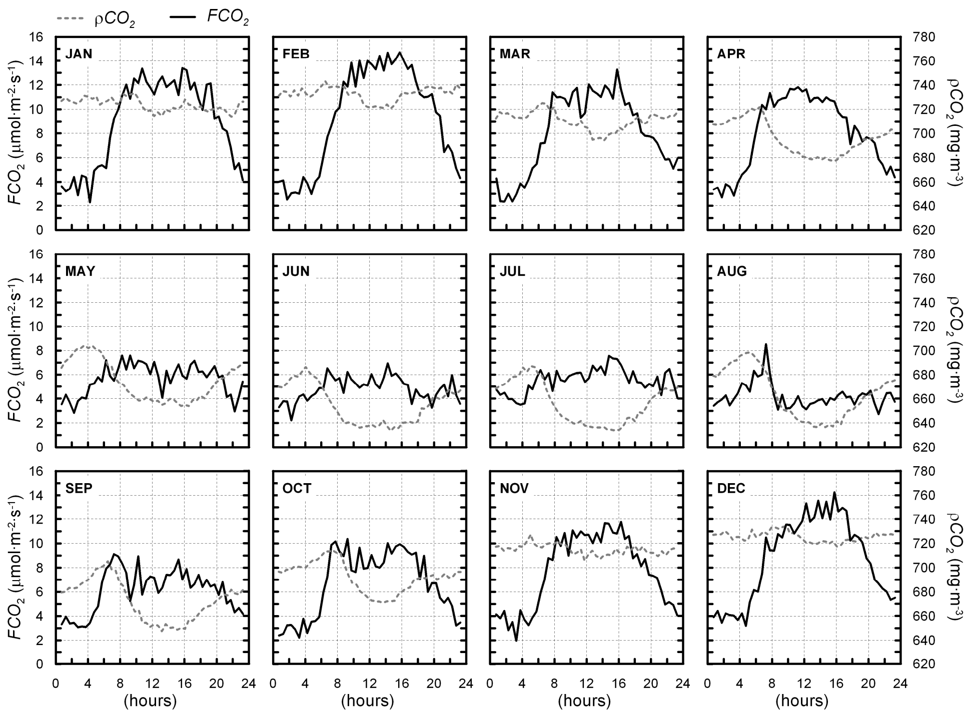


Fig. 6. Mean diurnal courses of carbon dioxide density ρCO_2, (grey dotted line) and turbulent flux FCO_2 (black solid line) calculated for months in the period July 2006 – July 2009 based on 30-minutes data

Mean diurnal course of FCO_2 was also calculated for whole analysis period (Fig. 7, solid line on upper graph). Known from the literature mean diurnal of FCO_2 course with two maxima represent morning and afternoon peak of car transport intensity (Coutts *et al*. 2007) is not observed in this case. Mean diurnal courses were also calculated for working days of week (from Monday to Friday, Fig. 7, intermittent line on upper graph) and for weekends (Saturday to Sunday, Fig. 7, grey lines on upper graph). In both cases FCO_2 flux was positive, but for weekends its values were significant lower and two maxima of CO_2 turbulent exchange can be observed in case of weekdays. This situation is caused by much less intensity of car traffic during weekends, and as a result mean maximum FCO_2 is lower during weekends by about 4 μmol m^{-2} s^{-1}. Mean diurnal courses of FCO_2 for seasons were also calculated (Fig. 7, lower graphs). Similar differences between mean diurnal variability of FCO_2 calculated for working days and weekends can be observed, with the exception of winter, when intensive emission of anthropogenic carbon dioxide related to car traffic and strong house heating dominates. In summer, minimum value of mean seasonal FCO_2 flux occurs during the day of weekend, which can be explained by low carbon dioxide emission generated by car traffic (related to summer holidays) and absorption by plants during the day.

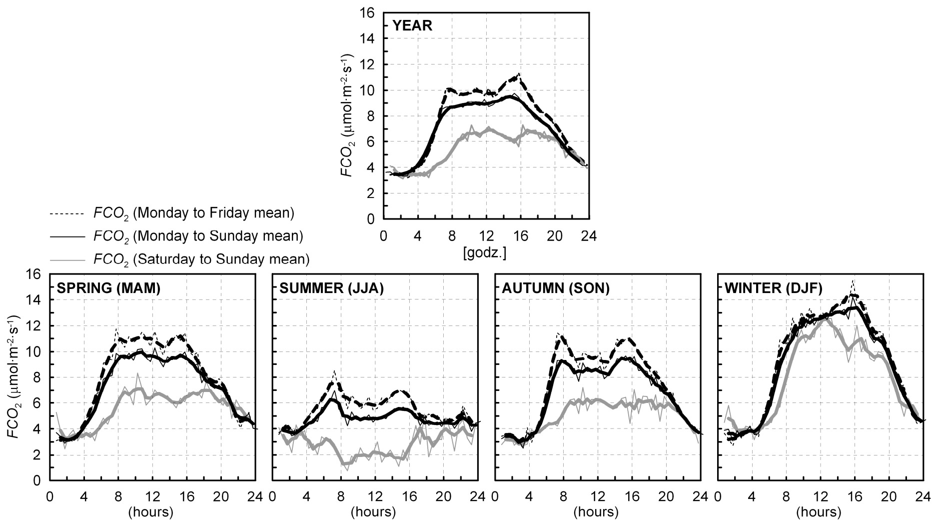


Fig. 7. Mean diurnal courses of turbulent flux FCO_2, in the period July 2006-July 2009 calculated for week (black line), working days (black dotted line) and weekends (grey line) and smoothed by 3-elements running average

Emission of carbon dioxide from urban surface is not spatially homogeneous, so mean carbon dioxide net flux was also calculated in relation with wind direction for the analysis period. Results of this calculation for 10 degree intervals of wind direction are presented in Figure 8 (middle graph). Asymmetry of FCO_2 is clearly visible with prevalence of eastern sector of wind. Air flow from the center of the city causes significantly more intensive FCO_2 of the order of 10-11 μmol m^{-2} s^{-1} at average. Carbon dioxide exchange is much less intensive in the case of air flow from the west sector, which is probably caused by not so dense building development (lower emission of CO_2 during house heating in winter) and by plants which during warm season have been absorbing CO_2. This disproportion determines diurnal courses of FCO_2 calculated for east and west wind sectors (fig. 8, right graph). In both cases mean FCO_2 is always positive, but in case of east air flow FCO_2 is much higher, especially at the afternoon when the difference reaches ~9 μmol m^{-2} s^{-1} in comparison with diurnal course calculated for air flow from the west part of city.

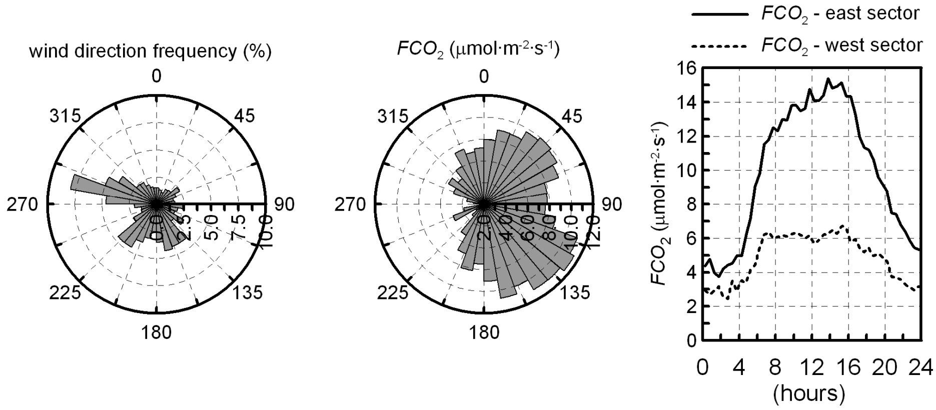


Fig. 8. Mean wind direction frequency by wind direction, turbulent flux FCO_2 by wind direction (both 10 degree intervals) and mean daily courses of FCO2 calculated for airflow from east and west sectors

SUMMARY AND CONCLUSIONS

Presented results of measurement carried out in Łódź reveal that above dense built-up city center emission of carbon dioxide prevails over absorption and this is not season dependent. Intensity of CO_2 exchange above the urban terrain is determined by anthropogenic sources of this gas (house heating, public transport, etc.). Exception to the rule is summer season, when the lowest anthropogenic emission of CO_2 during the year with absorption of this gas during photosynthesis process determines the lowest values of carbon dioxide net flux during year. Moreover, predominance of anthropogenic CO_2 sources over natural ones results in more intensive CO_2 exchange during weekdays, so specific, not observed in case of natural or agricultural surfaces, weekly variability of FCO_2 occurs.

REFERENCES

Baldocchi D., Finnigan J., Wilson K., Paw U.K.T., Falge E., 2000. On measurements net ecosystem carbon exchange over tall vegetation on complex terrain. Bound-Lay. Meteorol., 96, 257-291.

Coutts A.M., Beringer J., Tapper N.J., 2007. Characteristics influencing the variability of urban CO_2 fluxes in Melbourne, Australia. Atmos. Environ., 41, 51-62.

Fortuniak K., 2009. Energy balance of cities (in polish). University of Łódź Press, Łódź (in print)

Finnigan J.J., 2004. A re-evaluation of long-term flux measurement techniques Part II: coordinate systems. Bound-Lay. Meteorol., 113, 1-41.

Grimmond C.S.B., King T.S., Roth M., Oke T.R., 1998. Aerodynamic roughness of urban areas derived from wind observations. Bound-Lay. Meteorol., 89, 1-24.

Grimmond C.S.B., Oke T.R., 1999. Aerodynamic properties of urban areas derived from analysis of surface form. J. App. Meteorol., 38, 1262-1292.

Grimmond C.S.B., King T.S., Cropley F.D., Nowak D.J., Souch C., 2002. Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago. Environ. Pollut., 116, 243-254.

Kaimal J.C., Finnigan J.J., 1994. Atmospheric boundary layer flows: their structure and measurement. Oxford University Press, New York.

Kłysik K. 1996. Spatial and seasonal distribution of anthropogenic heat emission in Lodz. Poland, Atmos. Environ., 30, 3397-3404.

Kłysik K. 1998. The characteristics of urban areas in Łódź from a climatological point of view. *Acta Universitatis Lodziensis, Folia Geographica Physica*, 3, 173-185 (in polish).

Lee X., Black T.A., den Hartog G., Neumann H.H., Nesic Z., Olejnik J., 1996. Carbon dioxide exchange and nocturnal processes over a mixed deciduous forest. Agr. Forest Meteorol., 81, 13-29.

Lee X., Massman W., Law B., 2004. Handbook of Micrometeorology. A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht.

Moncrieff J.B., Massheder J.M., de Bruin H., Elbers J., Friborg T., Heusinkveld B, Kabat P., Scott S., Soegaard H., Verhoef A., 1997. A system to measure fluxes of momentum sensible heat, water vapour and carbon dioxide. J. Hydrol., 188-189, 589-611.

Moriwaki R., Kanda M., 2004. Seasonal and diurnal fluxes of radiation, heat, water vapour and carbon dioxide over suburban area. J. Appl. Meteorol., 43, 1700-1710.

Nemitz E., Hargreaves K.J., McDonald A.G., Dorsey J.R., Fowler D., 2002. Micrometeorological measurements of the urban heat budget and CO_2 emissions on a city scale. Environ. Sci. Technol., 36, 3139-3146.

Offerle B., 2003. The energy balance of an urban area: Examining temporal and spatial variability through measurements, remote sensing and modelling. PhD dissertation (manuscript).

Offerle B., Grimmond C.S.B., Fortuniak K., 2005. Heat storage and anthropogenic heat flux in relation to the energy balance of a central European city centre. Int. J. Climatol., 25, 1405-1419.

Offerle B., Grimmond C.S.B., Fortuniak K., Kłysik K., Oke T.R., 2006a. Temporal variations in heat fluxes over a central European city centre. Theor. Appl. Climatol., 84, 103-115.

Offerle B., Grimmond C.S.B., Fortuniak K., Pawlak W., 2006b. Intra-urban differences of surface energy fluxes in a central European city. J. App. Meteorol., 45, 125-136.

Pataki D.E., Emmi P.C., Forster C.B., Mills J.L., Pardyjak E.R., Peterson T.R., Thompson J.D., Dudley-Murphy, E., 2009, An integrated approach to improving fossil fuel emissions scenarios with urban ecosystem studies. Ecological Complexity, 6, 1-14.

Schmid H.P., 1994. Source areas for scalar and scalar fluxes. Bound-Lay. Meteorol., 67, 293–318.

Schmid H.P., Grimmond C.S.B., Cropley F., Offerle B., Su H-B., 2000. Measurements of CO_2 and energy fluxes over mixed hardwood forest in the mid-western United States. Agr. Forest Meteorol., 103, 357-374.

Schotanus P., Nieuwstadt F.T.M., DeBruin H.A.R., 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations. Bound-Lay. Meteorol., 26, 81-93.

Vellasco E., Pressley S., Allwine E., Westberg H., Lamb B., 2005. Measurements of CO_2 fluxes from the Mexico City urban landscape. Atmos. Environ., 39, 7433-7446.

Vickers D., Mahrt L., 1997. Quality control and flux sampling problems for tower and aircraft data. J. Atmos. Ocean. Tech., 14, 512-526.

Vogt R., Christen A., Rotach M.W., Roth M., Satyanarayana A.N.V., 2006. Temporal dynamics of CO_2 fluxes and profiles over a Central European city. Theor. Appl. Climatol., 84, 117-126.

Webb E.K., Pearman G.I., Leuning R., 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. Q. J. Roy. Meteor. Soc., 106, 85-100.

5. PRELIMINARY RESULTS OF RESEARCH ON VARIABILITY OF TROPOSPHERIC OZONE IN THE SOUTHERN PART OF THE WARSAW AGGLOMERATION *

Katarzyna Rozbicka, Tomasz Rozbicki, Małgorzata Kleniewska

Warsaw University of Life Sciences, Division of Meteorology and Climatology
ul. Nowoursynowska 166, 02-787 Warszawa
e-mail: tomasz_rozbicki@sggw.pl

INTRODUCTION

Nitrogen oxides in a significant way affect quality of atmospheric air especially in cities, both as primary pollutants and also as a factor causing secondary pollution, e.g. tropospheric ozone (O_3), peroxyacyl nitrate (PAN), which are considered to be more harmful for human health and the environment than primary pollution. Chemical changes of nitrogen oxides in the troposphere are connected with the phenomenon of photochemical smog. It commonly occurs in big cities all over the world. Above-average concentrations of ozone and other photochemical oxidants are also observed far from city centres, which is connected with the transport of pollutants in the atmosphere and not only with influence of emissions from traffic sources or from heating systems. The amount of air pollution with nitrogen oxides and tropospheric ozone, apart from emission of the pollutants (Skov *et al.* 1997), is to a large extent shaped by meteorological conditions (Godłowska, Tomaszewska 2002, 2006, Hoffman 1998). Meteorology determines the access of solar radiation, is responsible for dispersion of ozone and its precursors and sporadic transport of ozone from the stratosphere in frontal zones (Baertsch-Ritter *et al.* after Tomaszewska, Godłowska 2008). Meteorological conditions become particularly important in a situation of a photochemical smog hazard.

The goal of the study is to present changes in the concentration of tropospheric ozone in comparison with fluctuations of nitrogen oxide concentration, which is its precursor and with meteorological elements constituting catalysts of photochemical reactions such as solar radiation and air temperature.

*The research on atmosphere pollution with nitrogen oxides and tropospheric ozone in the southern part of the Warsaw agglomeration is conducted with the use of funds from the grant of the Ministry of Science and Higher Education.

MATERIAL AND METHOD

The research material comes from the automatic monitoring atmosphere station Ursynów SGGW (φ = 52°09' N; λ = 21°03' E; H_S = 102.5 m above sea level) located in the southern outskirts of Warsaw within well laid out urban area. The station is situated in the university campus of the Warsaw University of Life Sciences (SGGW) about 12 km south of the city centre. In the closest vicinity of the station there are two- and three-storey buildings of the University. The nearest tall buildings of housing developments in the Ursynów district are located about 1-3 km north, west and south of the building; thus, only easterly air does not move above residential areas with tall urban buildings. The main emission sources of pollutants for this station are motor vehicles moving along streets surrounding the SGGW university campus: Ciszewskiego Street (150 m to the south) and Nowoursynowska Street (100 m to the east) and Rodowicza "Anody" Street (about 300 m to the west). The main industrial source of pollutants is the chimney of the heat and power plant Siekierki located about 4 km north-east of the station. However, it should be noted that the level of gas pollutants of the atmosphere recorded at the Ursynów SGGW station is relatively low and permissible values are not exceeded.

The data on the concentration of atmospheric pollutants and meteorological data come from the period of the warm 6 months in 2009 (from April to September). The study used instantaneous values of nitrogen oxides concentration (NOx), ozone concentration (O_3) values of air temperature (t) and concentration of total solar radiation (SR) measured every hour during the daytime. UV photometric method is used to the ozone concentration measurement and chemiluminescence method was used to the oxides of nitrogene concentration measurement. Because formation of tropospheric ozone is related to solar radiation intensity, from the whole set of data two subsets of days with a characteristic course of the intensity of total solar radiation were separated. At a further stage of the analysis it turned out that better results will be achieved in the case of a more detailed division of the set of data, considering also the course of air temperature. Finally, four subsets of data, i.e. days, were separated for four types of the course of weather: with a high value of the intensity of total solar radiation and high temperature (type HH, with the letter H denoting high values of both elements), high radiation and low temperature (HL type, with the letter L denoting low values of the second element, i.e. temperature), low radiation and high temperature (type LH) and low value of the intensity of total solar radiation and low temperature (type LL). Categorisation of particular days into a specific subset depends on the value of average daily total solar radiation and average daily air temperature and half the value of standard deviation of these meteorological elements, according to the formulas presented in Table 1.

Table 1. Categorisation conditions of particular days into four subsets of data

Category of conditions	Type HH	Type HL	Type LH	Type LL
Solar radiation	$T_d > T_m + ½·s_T$	$T_d > T_m + ½·s_T$	$T_d < T_m – ½·s_T$	$T_d < T_m – ½·s_T$
Air temperature	$t_d > t_m + ½·s_t$	$t_d < t_m – ½·s_t$	$t_d > t_m + ½·s_t$	$t_d < t_m – ½·s_t$

explanations:
T_d – Daytime average value of intensity of total solar radiation,
T_m– Monthly average value of intensity of total solar radiation,
s_T – Standard deviation of intensity of total solar radiation,
t_d – Daytime average value of air temperature,
t_m– Monthly average value of air temperature,
s_t – Standard deviation of air temperature.

In order to determine the relationship between the concentration of tropospheric ozone and the concentration of nitrogen oxides and meteorological elements, regression analysis was used. For data from each month, correlation coefficients of pairs were calculated and also regression equations (multiple or linear) which best described the relationship were determined. The analysis was conducted with the use of the program Statistica.

RESULTS AND DISCUSSION

Strength of the relationship between tropospheric ozone concentration and the concentration of nitrogen oxides and the examined meteorological elements depends on correlation coefficients of pairs. The list of these coefficients was presented in Table 2. It is worth noting that in the case of days with high radiation and high temperature (type HH) and days with high radiation and low temperature (type HL) air temperature is the independent variable which is almost always best correlated with the level of ozone concentration. In the case of days with low radiation and high temperature (type LH) the concentration of nitrogen oxides is the variable and for days with low radiation and low temperature (type LL) in different months the highest values of correlation coefficient were obtained for different variables both for nitrogen oxides, radiation and also temperature.

Table 2. Correlation coefficients of pairs between the concentration of tropospheric ozone and the concentration of nitrogen oxides, solar radiation intensity and air temperature

Month	type HH			type HL			type LH			type LL		
	NOx	*SR*	*t*	NOx	*SR*	*t*	NOx	*SR*	*t*	NOx	*SR*	*t*
Apr	0,42	0,19	0,93	0,72	0,26	0,71	0,83	0,42	0,79	0,57	0,51	0,65
May	0,78	0,28	0,87	0,80	0,17	0,91	0,87	0,25	0,77	0,74	0,44	0,71
Jun	0,42	0,31	0,49	0,66	0,30	0,77	–	–	–	0,36	0,47	0,25
Jul	0,61	0,37	0,86	0,05	0,08	0,98	0,86	0,40	0,93	0,39	0,33	0,52
Aug	0,42	0,26	0,80	0,75	0,32	0,96	0,28	0,28	0,91	0,43	0,37	0,65
Sep	0,74	0,38	0,89	0,91	0,44	0,95	–	–	–	0,79	0,41	0,72

explanations:
NOx – oxides of nitrogen concentration in ppm,
SR – intensity of total solar radiation in W m^{-2},
t – air temperature in °C,

Tables 3-8 present regression equations and their coefficients of correlation and determination best describing the relationship between the concentration of tropospheric ozone and the considered independent variables. Tables 3-5 concern the subset of days with a high value of the intensity of total solar radiation and Tables 6-8 the subset of days with a low value of the intensity of total solar radiation. The determination coefficients of equations presented in Table 3 are lower than the coefficients in Tables 4 and 5. Comparison of the determination coefficients of the equations in Table 6 with the coefficients in Tables 7 and 8 leads to a similar observation. It shows usefulness of dividing the set of data into four subsets – additionally taking into account the criterion of temperature. High correlation coefficients obtained in the case of the majority of the equations show a strong relationship between the level of tropospheric ozone concentration and the considered independent variables. It means that at the Warsaw Ursynów SGGW station, where the level of gas pollution is relatively low, there occur reactions of nitrogen oxides, with participation of solar radiation and air temperature as catalysts of these reactions, which are characteristic for the formation of photochemical smog.

Table 3. Regression equations between tropospheric ozone concentration at Ursynów SGGW and chosen independent variables for high values of the intensity of total solar radiation

Month	n	Form of equation	R_{adj}^2	SE
Apr	78	$O_3 = 29,2 – 0,65·NOx + 1,69·t$	87,6	4,7
May	156	$O_3 = 21,3 – 1,19·NOx + 1,80·t$	80,5	6,0
Jun	156	$O_3 = 33,6 – 1,22·NOx + 7,39·10^{-3}·SR +0,36·t$	27,1	9,6
Jul	91	$O_3 = –13,4 – 1,10·NOx + 2,50·t$	66,0	8,3
Aug	130	$O_3 = –27,3 + 2,88·t$	70,8	7,2
Sep	91	$O_3 = –8,1 – 1,50·NOx + 2,34·t$	86,6	5,7

All relationships are statistically significant at the 99% confidence level
explanations:
n – number of observations (sample size)
R_{adj}^2 – determination coefficient (adjusted) for multiple (or simple) equation in %,
SE – standard error of estimation
O_3 – tropospheric ozone concentration in ppm,
NOx – oxides of nitrogen concentration in ppm,
SR – intensity of total solar radiation in W m^{-2},
t – air temperature in °C.

Table 4. Regression equations between tropospheric ozone concentration at Ursynów SGGW and chosen independent variables for high values of the intensity of total solar radiation and high temperature (type HH)

Month	n	nod	Form of equation	R_{adj}^2	SE
Apr	39	3	$O_3 = 17,9 – 0,55·NOx + 2,19·t$	89,0	3,6
May	91	7	$O_3 = –6,7 – 1,03·NOx + 3,1·t$	85,9	5,9
Jun	104	8	$O_3 = 12,4 – 0,95·NOx +1,29·t$	31,6	9,9
Jul	78	6	$O_3 = –55,1 – 0,57·NOx + 3,82·t$	75,2	7,5
Aug	91	7	$O_3 = –31,9 + 3,04·t$	64,5	8,2
Sep	78	6	$O_3 = –17,0 – 1,26·NOx + 2,69·t$	87,4	5,7

All relationships are statistically significant at the 99% confidence level
explanations:
nod – number of days of the month considered in the analysis.

Table 5. Regression equations between tropospheric ozone concentration at Ursynów SGGW and chosen independent variables for high values of the intensity of total solar radiation and low temperature (type HL)

Month	n	nod	Form of equation	R_{adj}^2	SE
Apr	39	3	$O_3 = 30{,}5 – 0{,}67 \cdot NOx + 1{,}67 \cdot t$	80,3	5,2
May	65	5	$O_3 = 16{,}8 – 0{,}61 \cdot NOx + 2{,}01 \cdot t$	91,0	2,6
Jun	52	4	$O_3 = 10{,}8 – 1{,}22 \cdot NOx + 2{,}31 \cdot t$	69,0	5,5
Jul	13	1	$O_3 = –31{,}2 + 3{,}20 \cdot t$	96,4	1,7
Aug	39	3	$O_3 = –32{,}8 + 3{,}72 \cdot t$	93,3	2,7
Sep	13	1	$O_3 = –17{,}4 – 9{,}50 \cdot 10^{-3} \cdot SR + 3{,}05 \cdot t$	93,5	2,9

All relationships are statistically significant at the 99% confidence level.

Table 6. Regression equations between tropospheric ozone concentration at Ursynów SGGW and chosen independent variables for low values of the intensity of total solar radiation

Month	n	Form of equation	R_{adj}^2	SE
Apr	78	$O_3 = 19{,}3 – 0{,}52 \cdot NOx + 0{,}030 \cdot SR\ \ +1{,}00 t$	61,2	8,6
May	91	$O_3 = 7{,}67 – 1{,}29 \cdot NOx + 2{,}07 \cdot t$	80,0	5,2
Jun	52	$O_3 = 23{,}6 – 0{,}55 \cdot NOx + 3{,}37 \cdot 10^{2} \cdot SR$	32,6	8,3
Jul	91	$O_3 = 22{,}2 – 1{,}89 \cdot NOx + 7{,}35 \cdot 10^{3} \cdot SR + 1{,}50 \cdot t$	50,7	6,7
Aug	91	$O_3 = –42{,}8 + 3{,}59 \cdot t$	71,1	5,7
Sep	65	$O_3 = 7{,}9 – 1{,}03 \cdot NOx + 0{,}0107 SR + 0{,}95 \cdot t$	75,3	3,9

All relationships are statistically significant at the 99% confidence level.

Table 7. Regression equations between tropospheric ozone concentration at Ursynów SGGW and chosen independent variables for low values of the intensity of total solar radiation and high temperature (type LH)

Month	n	nod	Form of equation	R_{adj}^2	SE
Apr	13	1	$O_3 = –2{,}9 – 1{,}01 \cdot NOx + 3{,}04 \cdot t$	87,0	4,6
May	26	2	$O_3 = 10{,}8 – 1{,}81 \cdot NOx + 2{,}18 \cdot t$	86,1	4,9
Jun	–	0	–	–	–
Jul	13	1	$O_3 = –16{,}0 – 1{,}56 \cdot NOx + 2{,}94 \cdot t$	96,9	2,1
Aug	13	1	$O_3 = –53{,}4 – 0{,}0224 \cdot SR + 4{,}45 \cdot t$	92,4	2,8
Sep	–	0	–	–	–

All found relationships are statistically significant at the 99% confidence level.

Table 8. Regression equations between tropospheric ozone concentration at Ursynów SGGW and chosen independent variables for low values of the intensity of total solar radiation and low temperature (type LL)

Month	n	nod	Form of equation	R_{adj}^2	SE
Apr	65	5	$O_3 = 12{,}4 - 0{,}40 \cdot NOx + 2{,}67 \cdot 10^{2} \cdot SR + 1{,}69 \cdot t$	63,2	8,5
May	65	5	$O_3 = 8{,}8 - 1{,}10 \cdot NOx + 1{,}85 \cdot t$	71,4	5,0
Jun	52	4	$O_3 = 23{,}5 - 0{,}55 \cdot NOx + 3{,}37 \cdot 10^{2} \cdot SR$	32,6	8,3
Jul	65	5	$O_3 = 11{,}0 - 1{,}40 \cdot NOx + 7{,}77 \cdot 10^{3} \cdot SR + 1{,}83 \cdot t$	33,4	7,1
Aug	65	5	$O_3 = -22{,}1 - 0{,}25 \cdot NOx + 2{,}51 \cdot t$	44,0	5,7
Sep	65	5	$O_3 = 7{,}9 - 1{,}03 \cdot NOx + 1{,}07 \cdot 10^{2} \cdot SR + 0{,}95 \cdot t$	75,4	3,9

All relationships are statistically significant at the 99% confidence level.

In Figures presented in the study, there are daily courses, being the average of a month, of ozone concentration, nitrogen oxides and the intensity of total solar radiation and air temperature. In the case of days with high solar radiation and high temperature (type HH) the course for April was chosen – the month for which regression equation has the highest determination coefficient out of all the months (89.0%). In the case of days with high solar radiation and low temperature (type HL) the chosen month was May, of which equation is also marked by high determination coefficient (91.0%). Both figures (Fig. 1 and Fig. 2) present a course of the examined elements typical for a sunny day. Concentration of nitrogen oxides reaches its peak in the morning (7 a.m.), then it drops and slightly increases in the afternoon (5-6 p.m.). Concentration of tropospheric ozone increases over the day and reaches the highest values in the early afternoon (2-3 p.m.), then it slightly drops but still remains at a relatively high level. The course of solar radiation intensity and temperature is typical for a day with anticyclonic weather. Diversification of the course of tropospheric ozone concentration is distinct, but the daily amplitude does not reach such high values as in the case of rural and suburban stations, which was shown, among others, by Tomaszewska and Godłowska (2008). In the case of days with low radiation and high temperature (type LH) the chosen month was July, for which regression equation has a very high determination coefficient (96.9%), and for days with low radiation and low temperature (type LL) September (determination coefficient of the obtained regression equation amounts to 75.4%). The shape of curves of the course of nitrogen oxides and ozone concentration in Figs. 3 and 4 is similar to the curves presented in Figs. 1 and 2, but the peak of ozone concentration is lower than in the case of sunny days, especially for type LL.

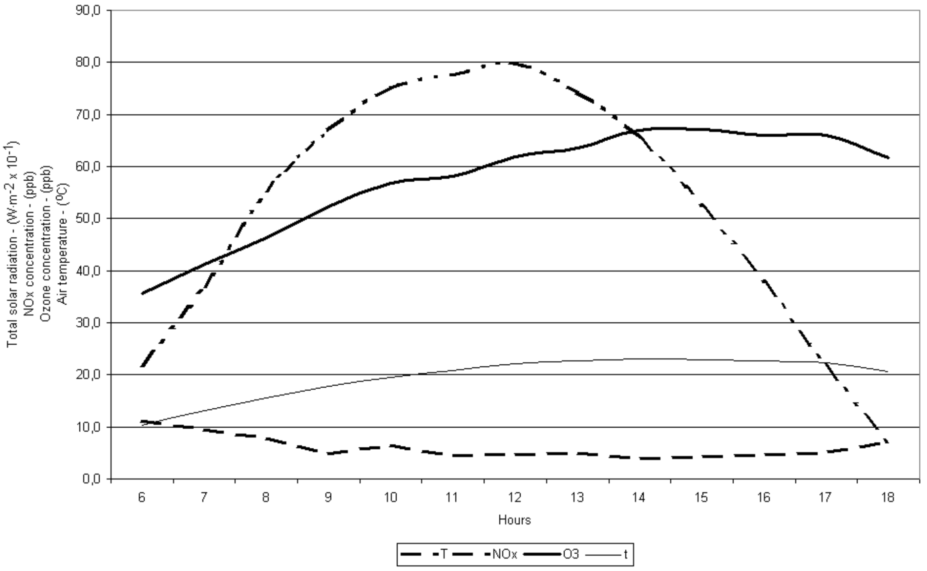


Fig. 1. Average daily course of tropospheric ozone concentration (O_3) in comparison with the intensity of total solar radiation (*T*), concentration of nitrogen oxides (NOx) and air temperature (*t*) in Ursynów for days with high radiation and high temperature (type HH) in April 2009

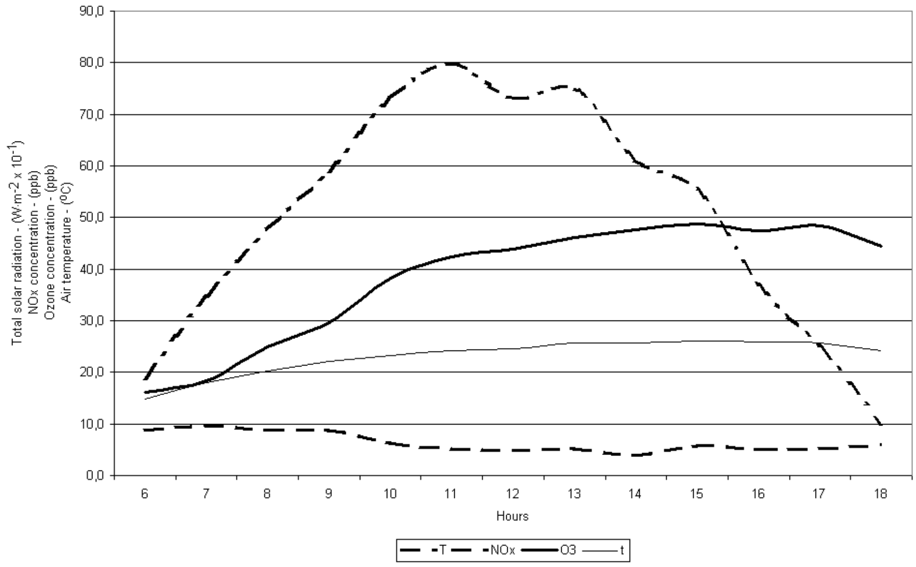


Fig. 2. Average daily course of tropospheric ozone concentration (O_3) in comparison with the intensity of total solar radiation (*T*), concentration of nitrogen oxides (NOx) and air temperature (*t*) in Ursynów for days with high radiation and low temperature (type HL) in May 2009

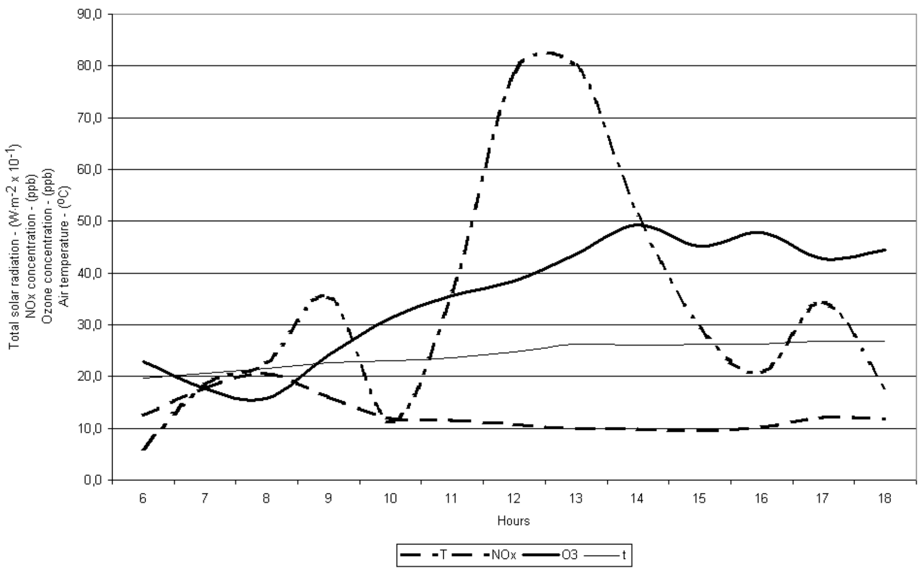


Fig. 3. Average daily course of tropospheric ozone concentration (O_3) in comparison with the intensity of total solar radiation (*T*), concentration of nitrogen oxides (NOx) and air temperature (*t*) in Ursynów for days with low radiation and high temperature (type LH) in July 2009

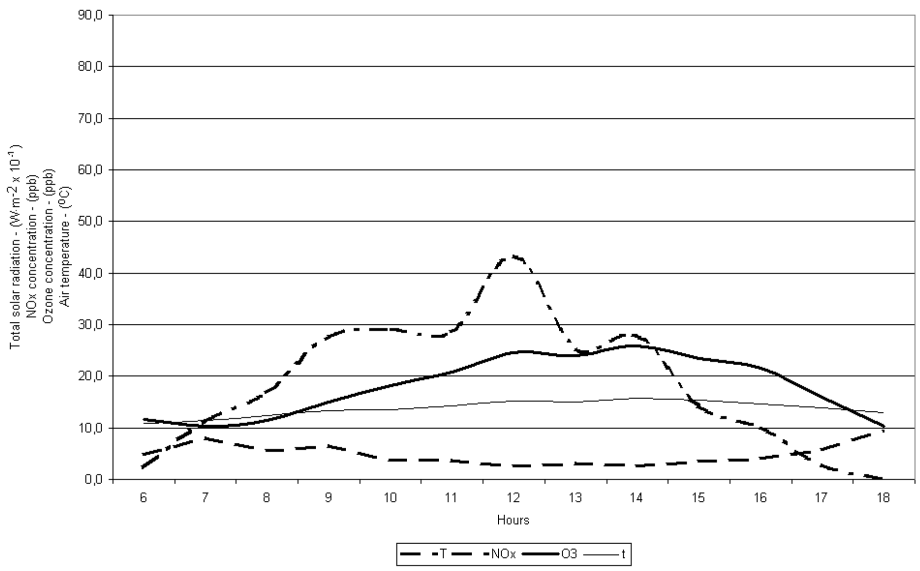


Fig. 4. Average daily course of tropospheric ozone concentration (O_3) in comparison with the intensity of total solar radiation (*T*), concentration of nitrogen oxides (NOx) and air temperature (*t*) in Ursynów for days with low radiation and low temperature (type LL) in September 2009

CONCLUSIONS

On the basis of the carried out analysis of variability of tropospheric ozone concentration in Warsaw-Ursynów SGGW the following statements can be formulated:

1. In the southern part of the Warsaw agglomeration in the vicinity of the Ursynów SGGW station there occur reactions characteristic of formation of photochemical smog. A decrease in concentration of nitrogen oxides is accompanied by an increase in ozone concentration of which peak takes place in the early afternoon.
2. On days with anticyclonic weather with high values of the intensity of total solar radiation, air temperature and concentration of nitrogen oxides determine formation of tropospheric ozone. It is shown by the analysis of correlation of pairs and the form of regression equations obtained for days with high solar radiation.
3. There is a strong relationship between the concentration of tropospheric ozone and the considered variables: the level of nitrogen oxides concentration and meteorological elements: air temperature and the intensity of total solar radiation. Regression equations describing these relationships usually have high determination coefficients.

The obtained results come from a short research period – the warm 6 months of 2009. It would be advisable to verify the relationships for a longer period encompassing several years. Lengthening of the research period will also enable separation of additional subsets of data – apart from days with high and low radiation and days with high and low temperature also days with a particular direction of air-mass flow. In the case of the location of the Ursynów SGGW station it seems to be appropriate. Easterly air masses do not move above the agglomeration and northerly masses before reaching the Ursynów district move above the centre of Warsaw – an area with high emission of atmospheric pollutants, especially traffic ones.

REFERENCES

Godłowska J., Tomaszewska A.M., 2002. Meteorological conditioning of maximum ozone concentration appearance in Poland (in Polish). Wiadomości IMGW, t. XXV(XLVI), 3.

Godłowska J., Tomaszewska A.M., 2006. The relation between 8-hourly average ozone concentration ($8O_3$) and types of circulation by J. Lityński in national ozone monitoring stations network (in Polish). Wiadomości IMGW, t. XXIX (L), 3-4, 3-16.

Hoffman Sz., 1998. The influence of NOx emission and meteorological conditions on troposheric ozone concentration (in Polish). Polish Academy of Science Institute of Environmental Engineering Committee of Environmental Engineering. Air protection in Theory & Application section III, Zabrze.

Skov H., Egelov A. H., Granby K., 1997. Relationship between ozone and other photochemical products at L1 Valby Danmark. Atospheric Environment, vol. 31, no. 5, 685-691.

Tomaszewska A. M., Godłowska J., 2008. Ozone In cities on the background of ozone in rural and suburbian areas (in Polish). Klimat i bioklimat miast. Wyd. Uniwersytetu Łódzkiego, 389-402.

6. URBAN-RURAL DIFFERENCES OF RADON (^{222}Rn) CONCENTRATION IN THE AIR SURFACE LAYER WITH REFERENCE TO METEOROLOGICAL CONDITIONS – PRELIMINARY ANALYSIS*

Agnieszka Podstawczyńska[1], Krzysztof Kozak[2], Jadwiga Mazur[2]

[1]Department of Meteorology and Climatology, University of Łódź
ul. Narutowicza 88, 90-139 Łódź
[2]Laboratory of Radiometric Expertise, Institute of Nuclear Physics , Polish Academy of Sciences
ul. Radzikowskiego 152 E, 31-342 Kraków
e-mail: apodstaw@uni.lodz.pl

INTRODUCTION

The natural radioactivity in the atmospheric boundary layer is mainly given by the radon and radon progeny. Radon (^{222}Rn) is an alpha-emitting radioactive gas with half-life of 3.82 days, daughter of radium ^{226}Ra that belongs to the uranium ^{238}U decay series. In Poland, radon inhalation is responsible for over 40% of the annual effective dose of ionizing radiation (Radiation Atlas of Poland 2005).^{222}Rn is released from the soil into the atmosphere (exhalation), where is dispersed mainly by turbulent diffusion. Radon exhalation mainly depends on geological formation, soil characteristics (radium content, permeability and porosity), meteorological parameters. Temporal variability of ^{222}Rn in the air near the ground in relation to weather elements (air pressure, wind velocity, precipitations, snow cover) and vertical mixing processes in the atmosphere were documented by various authors (Arnold et al. 2009, Duenas *et al*. 1996, Kataoka i Tsukamoto 1992, Porstendörfer *et al*. 1991). Radon and radon progeny have been proved to be useful as naturally occurring tracer of atmospheric transport and mixing conditions that can be used to inter the behavior of other atmospheric pollutants within the atmospheric boundary layer (Krajny *et al*. 2005, Perrino 2001, Sesana *et al*. 1998).

In Poland, the variation of atmospheric concentrations of radon with reference to meteorological conditions is not well documented due to lack of long-term measurements. Therefore, very few results have been published i.e. Kopcewicz (1968, 1979), Mazur (2008). Based on the measurements carried out in Warsaw during the period 1965-1969 the correlation between radon concentration in open air and air masses types, synoptic situations, precipitations and fog occurrences has been analyzed by Kopcewicz (1968, 1979). Mazur (2008) investigated the

---

*Funding for this research was provided by Polish Ministry of Science and Higher Education under grant N306 015 32/1011 in the period 2007-2010

radon exhalation from ground in connection with meteorological parameters and soil properties in the period 2003-2006.

The aim of the present study is to investigate the temporal variability of near-surface ^{222}Rn concentration with special consideration of radon build-ups in relation to urban-rural contrast of meteorological parameters (i.e. air temperature, thermal vertical gradient, wind speed) and urban heat island phenomenon.

MATERIAL AND METHODS

Study area and its subsoil radioactivity

Radon measurement sites are located in Central Poland (Łódź and Ciosny) and in the South (Kraków). In Łódź, ^{222}Rn is measured close to geometrical center of the city (φ = 51°46'N λ = 19°28'E) at urban automatic meteorological station of the Department of Meteorology and Climatology of Łódź University. Ciosny village is located in agrarian area, 25 km to the north of Łódź. ^{222}Rn levels in Ciosny are measured at rural automatic hydro-meteorological station (φ= 51°55' N'λ=19°24'E) of the Department of Hydrology and Water Management of Łódź University. In Kraków, ^{222}Rn concentration is registered in the north-west part of the city (suburban area), on Radon Study Field (φ = 50°05'N λ=19°53'E) of Laboratory of Radiometric Expertise, Institute of Nuclear Physics, Polish Academy of Sciences. The subsoil of investigated area consists of sand and clay (Łódź), glacial sand (Ciosny) and loessial soil on loess stratum to a deph of 8 m (Kraków).

Radium (^{226}Ra) activity concentration, the precursor of ^{222}Rn, in surface-layer soil at the measurement sites amounted to 13 $Bq \cdot kg^{-1}$ (Łódź), 4 $Bq \cdot kg^{-1}$ (Ciosny) and 22 $Bq \cdot kg^{-1}$ (Kraków) whereas the mean value of ^{226}Ra concentration in Poland equals 25 $Bq \cdot kg^{-1}$ (Radiation Atlas of Poland 2005).

Instrumentation and methods

The continuous measurements of ^{222}Rn concentration (in 60-minute intervals) in Łódź, Ciosny and Kraków were made using one AlphaGUARD® PQ2000PRO per one measurement point (ionization chamber, Genitron Instruments GmbH). The device was set up in a meteorological box at the height of 2 m above the ground from January 2008 to November 2009. In Central Poland, the following meteorological parameters analyzed in the present study were recorded simultaneously with radon levels: air temperature at height 2m and 0.2 m above the ground, wind speed, soil heat flux using HFP01 Heat Flux Plate (Campbell Scientific Ltd). The annual and daily courses of ^{222}Rn concentration in urban, rural and suburban were compared. The relationships between ^{222}Rn concentration and temperature lapse rate in the air stratum 2-0.2m were studied. The annual and seasonal means of 24-hour patterns of ^{222}Rn concentration were analyzed in relation to the courses of wind velocity, soil heat flux and air temperature. Urban-rural differences of radon levels and urban-rural differences of air temperature at the height 2m above the ground with special consideration of urban heat island phenomenon (a positive thermal anomaly of a city if compared to rural area) were presented. Additionally, the synoptic charts were analyzed to reveal the favorable mesoscale weather condition to increase of urban-rural differences of ^{222}Rn concentration.

RESULTS AND DISSCUSION

Outdoor ^{222}Rn concentrations were distinguished by high variability and the radon levels through the period 01.01.2008-30.11.2009 did not exceed 21 Bq·m^{-3} in Łódź (absolute maximum (AMAX) occurred on 17th September, 2009 at 04.00 a.m.; arithmetic mean (AM) : 5 Bq·m^{-3}) and 40 Bq·m^{-3} in Ciosny (AMAX on 31st May, 2009 at 08.00 a.m.; AM : 6 Bq·m^{-3}) and 86 Bq·m^{-3} in Kraków (AMAX on 08th October, 2009 at 09.00 a.m.; AM : 10 Bq·m^{-3}). The annual pattern of ^{222}Rn concentrations characterized an increase from spring to autumn with a minimum in March at 3 stations (Fig. 1). The annual variability of mesoscale weather conditions corresponded with atmospheric concentrations of radon e.g. in February and March 2008 and 2009 radon build-ups were rare and the months distinguished high frequency of atmospheric instability resulting in cyclonic weather with exchange air masses. The summer and autumn months in 2008 and 2008 characterized more frequency of anticyclonic, sunny weather with light wind and the increase of radon concentrations was observed.

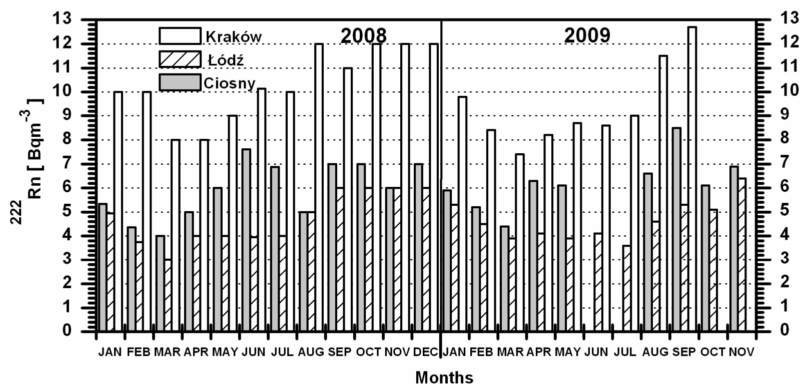


Fig. 1. Mean monthly radon (^{222}Rn) concentration in the air at the height 2 m above the ground in Ciosny, Łódź and Kraków in the period 01.01.2008-30.11.2009

The daily pattern of ^{222}Rn concentration was revealed with a maximum at 06.00 a.m. (Ciosny and Kraków) and at 07.00 a.m. (Łódź), and a minimum at 03.00 p.m (Ciosny and Kraków) and at 05.00 p.m. (Łódź), Figure 2. The various authors i.e. Arnold (2009), Baciu (2005), Duenas et al. (1996), Porstendörfer et al. (1991), Winkler et al. (2001) documented this diurnal variation of ^{222}Rn levels in the air resulted from the formation of a surface thermal inversion at night and an increase of turbulence in the daytime mixing layer. The urban station (Łódź) distinguished the lowest mean daily amplitude of ^{222}Rn concentration (1 Bq·m^{-3}) and one hour delay of the extremely daily values in relation to rural and suburban site (Fig. 2). The differences in the diurnal cycle between urban and rural sites resulted from the strong and fast radiative cooling of the rural site during the night, resulting in a surface thermal inversion layer that trapped radon near the surface. Differences between the rural and urban site disappeared in daytime when mixing processes in the lower atmosphere developed.

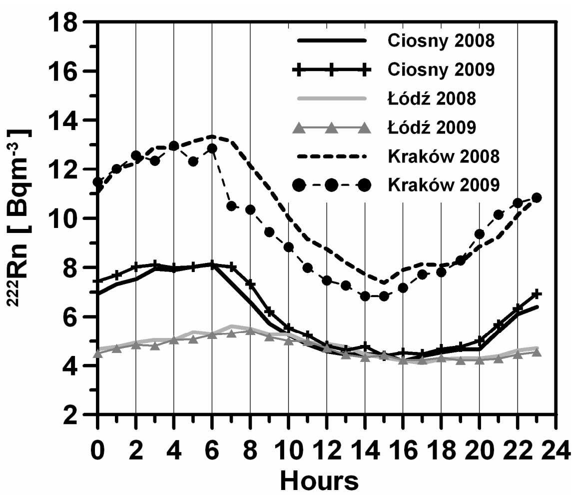


Fig. 2. Mean daily course of hourly radon (^{222}Rn) concentration in the air at the height 2 m above the ground in Ciosny, Łódź and Kraków in the period 01.01.2008-30.11.2009

Figure 3 shows the annual variability of air temperature lapse rate in the air stratum 2-02.m above the ground at urban (Łódź) and rural (Ciosny) sites in relation to ^{222}Rn concentration. Ciosny characterize increase of a nocturnal surface thermal inversion with lapse rate over 3ºC in May, June and July when maximum radon levels were measured (Fig. 3). In Łodź, the surface thermal inversions and radon build-ups were not observed in this period (Fig. 3). The maximum contrasts of ^{222}Rn levels between Łódź and Ciosny, exceed – 20 Bq m^{-3} occurred from April to September with maximum frequency in June, July and September (Tab. 1).

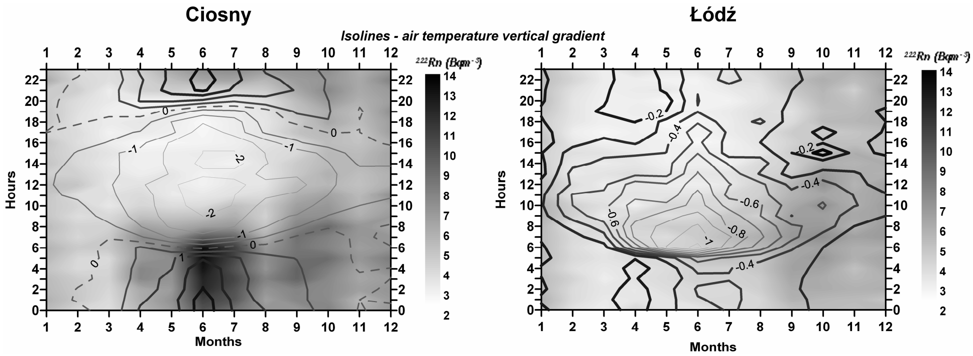


Fig. 3. Annual course of hourly radon (^{222}Rn) concentration in the air at the height 2 m above the ground and hourly air temperature vertical gradient in the air stratum 2-0.2 m (ºC) above the ground in Ciosny and Łódź in 2008

Table 1. Frequency (%) of hourly differences of ^{222}Rn concentration ≤ –10 Bq m^{-3} between Łódź and Ciosny in the period 01.01.2008-30.11.2009 (A). Absolute maximum of differences of hourly ^{222}Rn concentration in Bqm^{-3} between Łódź and Ciosny (B)

		Jan	Feb	Mar	Apr	May	Jun
2008	A	0.0	0.0	0.5	3.2	4.3	14.0
	B	–9.0	–10.0	–14.0	–17.0	–21.0	–28.0
2009	A	1.2	1.2	0.1	6.8	5.7	–*
	B	–19.0	–16.0	–10.0	–23.0	–35.0	–

		Jul	Aug	Sep	Oct	Nov	Dec
2008	A	10.0	2.0	2.0	3.0	0.5	2.0
	B	–31.0	–23.0	–24.0	–19.0	–16.0	–18.0
2009	A	–	7.0	12.2	1.5	1.4	–
	B	–	–22.0	–26.0	–17.0	–16.0	–

* lack of data.

In these months, the urban heat island effect (UHI, a positive thermal anomaly of urban area if compared to rural area) was very frequent with maximum of intensity amounted 8-9^{o}C (Fig. 4). The heat surplus at urban site caused strong vertical mixing of air and decrease of ^{222}Rn concentration near the ground in Łódź whereas at rural site a strong surface thermal inversion occurred (lapse rate in the air stratum 2-0.2 m reached 5^{o}C) and it trapped radon in the air surface layer. The highest urban-rural contrasts of ^{222}Rn levels and the clear 24-hour pattern of radon concentrations were registered during anticyclonic type weather conditions with a weak increasing pressure trend, wind speed <2 m s^{-1}, a high positive thermal gradient between 2 m and 0.2 m height (temperature inversion) indicating strong stable atmosphere.

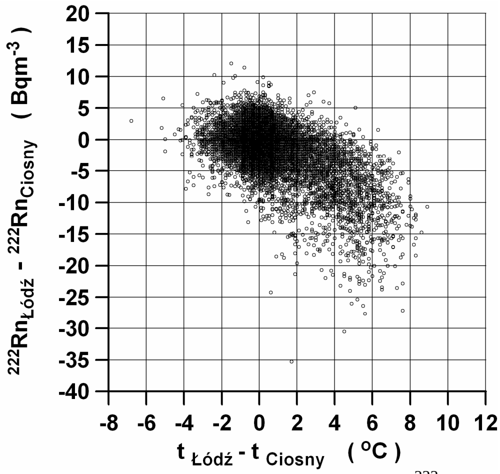


Fig. 4. Urban-rural (Łódź and Ciosny stations) differences of radon (^{222}Rn) concentration in the air at the height 2 m above the ground in relation to urban-rural air temperature differences at the height 2 m in the period 01.01.2008-30.11.2009

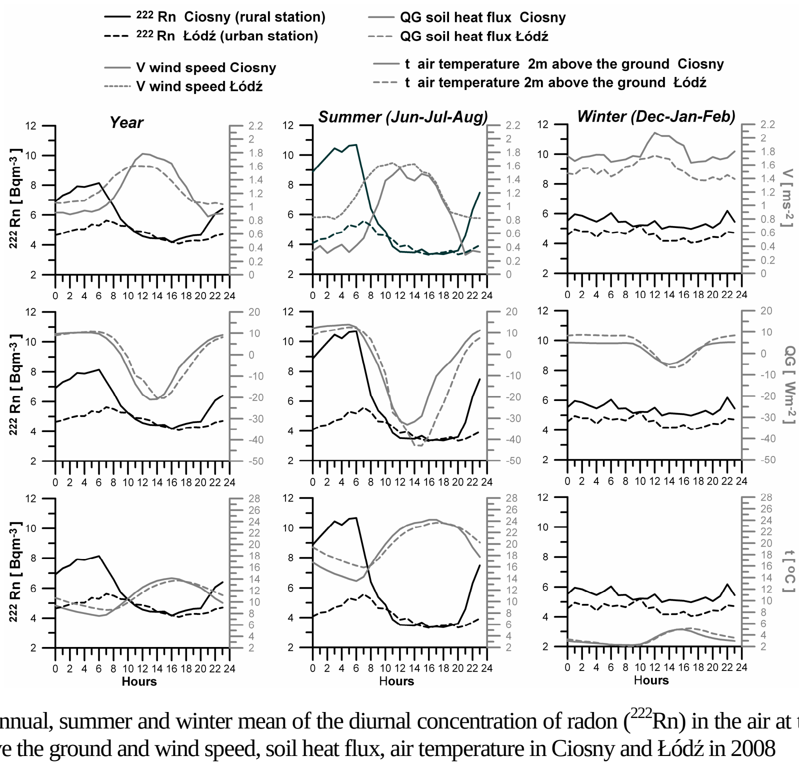


Fig. 5. Annual, summer and winter mean of the diurnal concentration of radon (^{222}Rn) in the air at the height 2 m above the ground and wind speed, soil heat flux, air temperature in Ciosny and Łódź in 2008

Figure 5 shows the mean daily variability of ^{222}Rn concentration with reference to the daily courses of wind speed, soil heat flux and air temperature over the whole year, summer and winter. As can be seen in Figure 5, summer is distinguished by more clear daily pattern and higher daily amplitudes of ^{222}Rn levels at rural station than in Łodź whereas this character of variability disappear in winter at both stations.

In general, the diurnal variation of near-surface ^{222}Rn levels varied approximately in phase with the soil heat flux and out of phase with wind speed (i.e. mechanical mixing in the boundary layer) and temperature (Fig. 5).

CONCLUSIONS

1. Analysis of two-year measurements of ^{222}Rn concentration measured at the height 2 m above the ground at urban and rural sites shows that outdoor radon levels are related to local and mesoscale weather conditions.
2. ^{222}Rn concentration increased at night stronger at rural station than in Łódź due to the formation of a surface-based inversion. Increase of turbulence in the daytime strongly reduced ^{222}Rn concentration at both stations.
3. In winter, radon levels at the urban and rural stations did not vary significantly over diurnal cycle because of strong atmospheric mixing.
4. ^{222}Rn build-ups occurred at night and increased with stable atmospheric conditions from spring to autumn with a maximum during intensive urban heat island. Anticyclone type weather with a weakly increasing pressure is favorable for the accumulation of radon near the ground.
5. The increase of ^{222}Rn concentration was observed together with the increase of soil heat flux and the increase of temperature lapse rate in the air stratum 2-02.m above the ground.
6. The daily course of ^{222}Rn concentration was characterized by the opposite pattern with air temperature and wind speed
7. The urban-rural contrast of meteorological parameters (i.e. air temperature, thermal vertical gradient, wind speed) can be used to determine near-surface radon build-ups.

REFERENCES

Arnold D., Vargas A., Ortega X., 2009. Analysis radon progeny concentration measured at the Spanish radioactive aerosol automatic monitoring network. Applied Radiation and Isotopes 67, 833-838.

Baciu A.C., 2005. Radon and thoron progeny concentration variability in relation to meteorological conditions at Bucharest (Romania). Journal of Environmental Radioactivity, 83, 171-189.

Duenas C., Perez M., Fernandez M.C., Carretero J., 1996. Radon concentration in the surface air and vertical atmospheric stability in the lower atmosphere. Journal of Environmental Radioactivity, 31, 87-102.

Kataoka T., Tsukamoto O., 1992. Variation of ^{222}Rn concentration in outdoor air due to variation of the atmospheric boundary layer. Radiation Protection Dosimetry, vol.45, No.1/4, 403-406 .

Kopcewicz T., 1968. O wpływie rodzaju mas powietrza na koncentrację naturalnych radionuklidów – pochodnych radonu i toronu – w przyziemnej warstwie powietrza (in Polish). Przegl. Geofiz., z.4 333-344.

Kopcewicz T., 1974. O zmianach promieniotwórczości naturalnej powietrza (in Polish). Przegl. Geofiz, z.3-4, 181-203.

Krajny E., Ośródka L., Skowronek J., Skubacz K., Wojtylak M., 2005. Diurnal variation of the mixing-layer height and polonium concentration in the air. Int. J. Environment and Pollution, vol. 25, 95-104

Mazur J., 2008. Dynamics of the process of radon exhalation from ground in connection with meteorological parameters and soil properties (in Polish), IFJ PAN Report No. 2014/AP (Ph. D. thesis), Kraków, 2008, http://www.ifj.edu.pl/publ/reports/2008/2014.pdf (in Polish).

Perrino C., Pietrodangelo A., Febo A., 2001. An atmospheric stability index based on radon progeny measurements for the evaluation of primary urban pollution. Atmospheric Environment, 35, 5235-5244.

Porstendörfer J., Butterweck G., Reineking A., 1991. Diurnal variation of concentration of radon and its short-lived daughters in the atmosphere near the ground. Atmospheric Environment, 25, 709-713.

Radiation Atlas of Poland 2005. Central Laboratory for Radiological Protection. Environmental Monitoring Books 2006.

Sesana L., Barbieri L., Facchini U., Marcazzan G., 1998. ^{222}Rn as a tracer of atmospheric motions: a study in Milan. Radiation Protection Dosimetry, 78, 65-71.

Winkler R., Ruckerbauer F., Trautmannsheimer M., Tschiersch J., Karg E., 2001. Diurnal and seasonal variation of the equlibrium state between short-lived radon decay products and radon gas in the ground-level air. Radiat. Environ. Biophys., 40, 115-123.

7. TREE CANOPY LEAF AREA INDEX (LAI) MEASUREMENTS WITH THE HEMISPHERICAL PHOTOGRAPHY AT A TUCZNO FOREST

Bogdan H. Chojnicki[1], Paweł Strzeliński[2], Alina Danielewska[1], Marek Urbaniak[1], Marcin Baran[1]

[1]Meteorology Department, Poznan University of Life Sciences
ul. Piatkowska 94, 60-649 Poznań, Poland
[2]Forest Management Department; Poznan University of Life Sciences
ul. Wojska Polskiego 71C, 60-625 Poznań, Poland

INTRODUCTION

Understanding different biochemical and physiological processes in such a complicated ecosystem like forest, requires precise and detailed research into all of its components. Light, thermal and moisture conditions within the forest canopy are strongly related with the carbon, water and energy cycles. Although the factors mentioned above are extremely important, such parameter like canopy structure cannot be neglected. In recent years several measurement techniques such as: gap fraction analyzes (GFA), allometric techniques (AT), terrestrial laser scanning (TLS) have been developed for the purposes of the above mentioned research. Within the scope of GFA method the hemispherical photography (HP) can be distinguished. The application of HP technique allows describing precisely such characteristics (variables) like: leaf area index (LAI) (Martens *et al.* 1993, Mitchel *et al.* 1993, Chen *et al.* 2006), spatial and temporal variability of light in forest understory (Clark *et al.* 1996), forest canopy architecture (Fournier *et al.* 1997), light environment in old growth forest (Weiss 2000). The HP is commonly used as a standard and relatively simple method for the LAI estimation, which is one of the basic indexes in the plant community ecophysiological research. Hemispherical photograph provides a permanent record and therefore, is a valuable source of such information as position, size, density, and distribution of canopy gaps. It is possible to capture the species-, site- and age-related differences in the canopy architecture, basing on light attenuation and contrast between the features within the photo (Jonckheeere *et al.* 2004).

The LAI index estimation is suitable for the assessment of canopy development and structure stage over time, depending on the species of trees and different environmental conditions. LAI calculation, in the HP technique, is based on assessment of the proportion of visible sky as the function of sky covered by tree canopy. In other words LAI can be defined as the leaf area per a ground area unit which would produce the observed gap fraction distribution, taking into consideration a random leaf surface angle and the extent to which the examined area is covered. Depending on the ecosystem: forest, grassland, wetland or cropland, HP methodology will have several limitations related to the plants height, age and canopy structure. One of the HP method limitations is the necessity of repetition of the photographs taken at the measurement area. For the LAI estimation at one marked point three images are necessary, which are subsequently subject to further analysis. Taking into consideration the number of obtained photos, the manual gap fraction calculation is highly laborious. Recently, numerous commercial software packages have been developed, as well as freeware programs that were consequently used for the numerical fraction calculations, such as: CI-110, CIMES, Gap Light Analyser, HemiView, RGBFisheye, Solarcalc, Winphot and WinSCANOPY (Jonckheere *et al.* 2005, Strzeliński 2006).

The TLS technique, unlike GFA (a passive system), is an active system of data collecting. The distinction between TLS and GFA is based on a different source of radiation. GFA takes advantage of a solar radiation reflection recorded by a sensor which is usually a lens of a camera. The TLS methodology measurement is based on the recording of laser radiation beam which was reflected by the given object. TLS system allows to obtain the precise map of features of the landscape as well as the representation of its natural elements (trees, seedlings) by recording the coordinates of XYZ points. The coordinates are described on the basis of the distance measured between the laser instrument and the examined element together with the vertical and horizontal angles of the beam. As a result of a single scan the so called cloud of points is obtained. In respect of methodology the scanner is similar to the total station equipment (like a laser radar) but it is totally automatic. The scanner is able to obtain the information about the examined elements at a rate of several thousand points per second (Tompalski and Kozioł 2008, Zawiła *et al.* 2008).

The main aim of this paper is the presentation of HP and TLS measurements conducted in Tuczno 52-years Scots Pine (*Pinus sylvestris L.*) forest in 2009. Moreover, the basic description of Tuczno site will be provided.

MATERIAL AND METHODS

Site description

The HP and TLS measurements were taken in Tuczno forest experimental site which is located in Tuczno Forest District (North-West of Poland, 53º11’N, 16º5’E) (Fig. 1).

The examined canopy is composed of 52-years old Scots pine (*Pinus sylvestris* L.) and birch (*Betula pendula* ROTH) trees which cover 99% and 1% of the area, respectively. The average diameter of a tree at the breast height (DBH) is 21 cm and the average tree height is about 20 m. The average annual precipitation and air temperature observed at this site are 570 mm and 7.6ºC, respectively. Western wind direction is prevailing in Tuczno. The under canopy vegetation consists mainly of beeches (*Fagus sylvatica* L.) and hornbeams (*Carpinus betulus* L.).

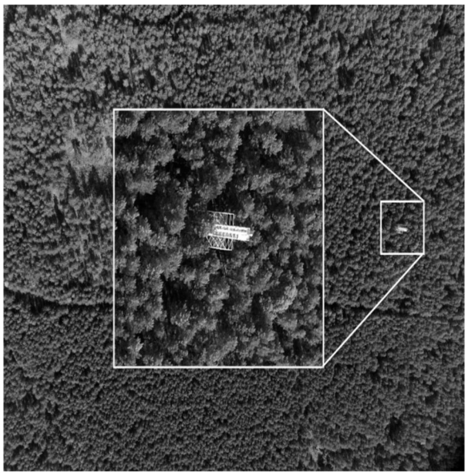


Fig. 1. a) The EC openwork construction, based on a reinforce concrete landing (photo: P. Strzeliński). b) The EC tower air view photo at Tuczno Forest District. In the quarter the location of EC tower used for CO_2 measurement has been presented (195j forest department) (photo Geomar)

Micrometeorological measurements

The eddy covariance (EC) measuring system consists of two instruments: an open path infrared gas analyzer IRGA Li-7500 (Li-Cor, Lincoln, NE, USA) and a three-dimensional asymmetric sonic anemometer CSAT3 (Campbell Scientific, Logan, UT, USA). Both instruments operate at a 20 Hz sampling rate. Moreover, Photosynthetic Photon Flux Density (PPFD) is measured by PAR Quantum sensor (SKP 215) (Skye, UK). All sensors are connected to a data-logger CR5000 (Campbell Scientific, Logan, UT, USA). Basic meteorological parameters are measured by an automatic meteorological station WXT510 (Vaisala, Helsinki, Finland).

Terrestrial laser scanning (TLS)

Fig. 2. 3D FARO scanner view. The EC tower in the background

The terrestrial laser scanning was chosen as it can precisely measure the selected trees' parameters as well as project the accurate map of the landscape features in Tuczno site. The FARO Laser Scanner LS HE880 (Faro, Lake Mary, Florida, USA) was used for this purpose. The scanning was conducted in 71 selected points in 2008 and 41 points in 2009. The example of a 3D FARO scanner view is presented in Figure 2. These points dotted about the 100 m transects facing North, South, East, West, North-West and South-West from the main tower (Fig. 3). The coordinates of each location were established with a GPS receiver (Trimble, GeoExplorer XT CE). The laser scanning was made at ¼ of scanner's full resolution (file size about 150 MB).

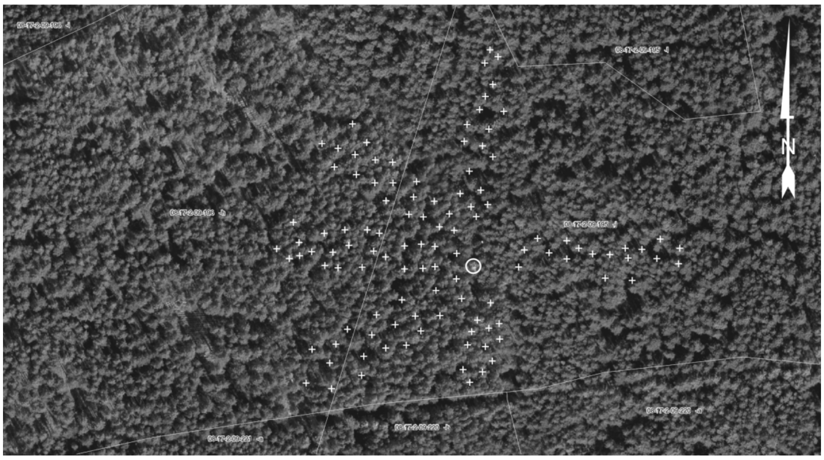
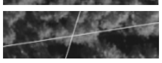


Fig. 3. The scanning location map in the ortophotomap background

 – EC tower,  – measuring points,

– forest section registration number in the State Forests National Holding data base,

 – forest section border.

Hemispherical Photography (HP)

Two HP applications have to be mentioned as a historical background. Firstly, the measurements of cloudiness conducted by Hill (1942), which were the initial measurements by means of HP also called fisheye photography. Secondly, in the 1950-s and 1960-s HP was used for the physiological studies in forest ecosystem by Evans and Coombe (1959) and Anderson (1964). From the mid-1970s onwards HP was applied for forest regeneration in gaps, the so-called 'gap-phase dynamics', which has grown to become a major focus for both temperate and tropical forest ecology (Watt 1947). In the 1990s HP was commonly used in the physiological studies of various ecosystems. Currently, the hemispherical photography is used mainly to investigate leaf area index and forest canopy structure, however, the absolute amount of light reaching the forest canopy surface as well as forest understory can also be estimated. (Martens *et al.* 1993, Kucharik *et al.* 1998a, 1998b, Gower *et al.* 1999, Hyer *et al.* 2004). The scientific basis of the method is the so called “threshold” – a selection (finding) of an optimum brightness value for the individual pixels of the photograph as the threshold which allows distinguishing between the vegetation and sky patches (Jonckheere *et al.* 2004).

In Tuczno forest site, HP was taken simultaneously with the TLS at all 112 measuring points. At each of them at least three HP repetitions were taken. The digital camera LR Canon EOS 5D (12MP matrix) and glass lens Sigma 8mm f/3.5 DG EX FISH EYE were used during the field research.

The obtained photos were analyzed with the use of the Gap Light Analyzer software. The research produced the following plant canopy characteristics:

- forest canopy transmittance of direct (CTdir) and diffused (CTdiff) light,
- canopy openness (CO),
- leaf area index (LAI),
- spatial variability of canopy foliage,
- photosynthetic active biomass.

The application of digital HP resulted directly in the estimation of the canopy openness and the measurement of absolute value of light reaching the forest understory, and consequently the value of leaf area index. The equipment included a 180 degree view angle eye lens and a digital camera, which were applied for forest canopy studies on previous occasions (Chan *et al.* 1986, Wagner 1994, Frazer *et al.* 1999, Englund *et al.* 2000, Inoue *et al.* 2004). The obtained hemispherical images were processed with the use of the Gap Light Analyzer ver. 2.0 software (Fig. 4).

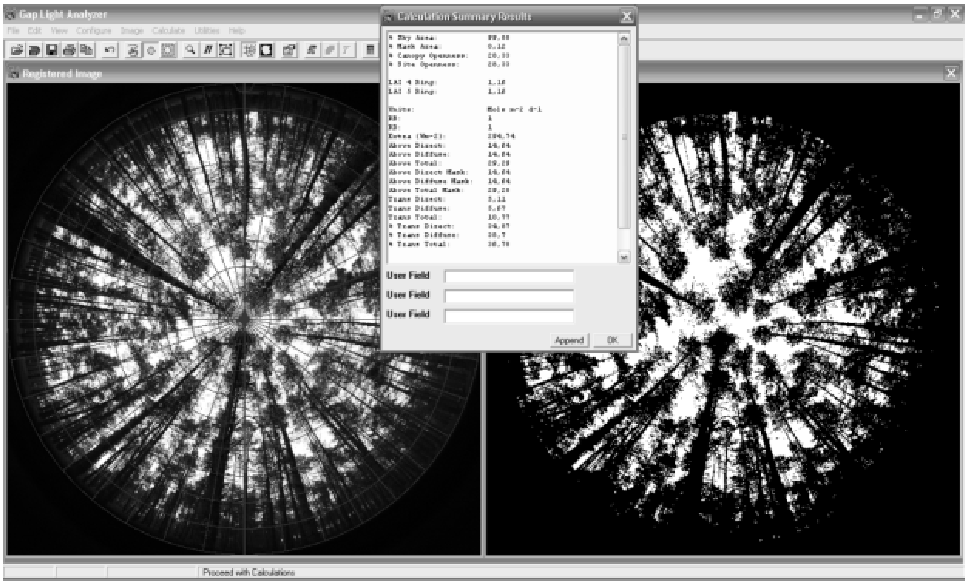


Fig. 4. The example of a single hemispherical photo analysis by the Gap Light Analyzer version 2.0 software

Traditional biomass measurements

The traditional biomass measurements were conducted at 112 measuring points determined in 6 transects (N, S, E, W, N-W, S-W) from the tower. The following basic parameters were measured on a surface in the shape of a circle (ray 7.98 m and the surface 200 m^2) between the marked points:

- the DBH of the trees which were inside every circular surface,
- the height of the three trees which were in the nearest distance from the middle of the surface).

RESULTS FROM TUCZNO FOREST SITE

Leaf Area Index (LAI)

In the examined forest stand the measured LAI index varied within the range of 0.87 to 1.50. The average values of measurements are presented in the Table 1. for the following points respectively:

- Ring 4 (calculated for the angle between zenith and 60° above the horizon) – LAI is 1.14,
- Ring 5 (calculated for the angle between zenith and 75° above the horizon) – LAI is 1.23.

Taking into consideration the fact that the HP technique is used very seldom in Polish pine tree stands, hence there are no comparative data, the results presented in the Table 1. should be compared with the data from LAI-2000 Plant Canopy Analyzer equipment (PCA) (www.licor.com). The comparison indicates that the estimation of leaf area index by means of HP technology may be underrated (by about 30-40%) in relation to the results obtained from LAI-2000 PCA (Strzeliński and Jagodziński 2010).

Table 1. The calculation of basic HP parameters around the Tuczno EC Tower

Statistical measure	Site open (%)	LAI 4 (1)	LAI 5 (2)	Transmission (μmol m^{-2} day^{-1})			Transmission (%)		
				dir.	dif.	tot.	dir.	dif.	tot.
n	335	335	335	335	335	335	335	335	335
Mean	28.07	1.14	1.23	5.53	5.85	11.37	37.74	39.95	38.84
Max	32.59	1.40	1.50	7.26	6.67	13.49	49.61	45.54	46.07
Min	23.70	0.87	1.02	3.94	5.16	9.33	26.89	35.25	31.86
Standard deviation	1.82	0.09	0.12	0.60	0.32	0.81	4.07	2.15	2.77
Coefficient of variation	0.98	1.02	0.98	1.06	0.96	1.01	1.06	0.96	1.01

(1) – results for ring 4 (calculated for the angle between zenith and 60^{o} above the horizon),
(2) – results for ring 5 (calculated for the angle between zenith and 75^{o} above the horizon).

The LAI data from Tuczno site were also compared with the data from forest sites across Europe which were published in the literature (Tab. 2). According to this comparison the LAI values for Tuczno site are the lowest. The difference is particularly visible in comparison with Hyytiälä (Finland) forest station. Such large differences in LAI values stem from the 10-year difference in tree age in the examined site and higher latitude. Furthermore the HP is related to the different level of clumping in forest canopies, dependently to the tree species (coniferous, broadleaves) and age. As the described technique makes use of large footprint (360^{o}) the appropriate amount of needle area in a shoot cannot be detected. This situation increase with the forest canopy development when the shoot is too dense to allow light penetration for deriving gap fractions (Gonsamo and Pellikka 2009). Additionally, the ground slope influence the LAI estimation. This phenomena can be found in Norunda site, where elevation is about 45 m. The high LAI values in the Sweden site are also related with the forest spices, which is mixed evergreen coniferous forest with 5% admixture of broadleaf spices. Similar forest species composition can be found in Loobos (Holland). According to the previous statements expressed in the current paper, also the applied measurement techniques influence the obtained results. The HP underestimate the LAI values, in comparison with LAI-2000 PCA methodology (about 30-40%), which can be one of the explanation for the above differences.

Table 2. The mean LAI values across European forest measurement sites from CARBOEUROPE-IP project data base (http://gaia.agraria.unitus.it/database/carboeuropeip)

Site location	Forest stand species	Age (years)	Mean air temp. (°C)	Precip. (mm)	Elevation (m)	LAI
Hyytiälä (Finland)	Pine (Pinus sylvestris) 100%	44	3.8	709	181	5.7
Norunda (Sweden)	Pine (Pinus sylvestris) 63%, Spruce (Picea abies) 33%, Birch (Betula pendula) 3%, Alder (Alnus glutinosa) 1%	105	6.1	527	45	4.3-4.9
Loobos (Holland)	Pine (Pinus sylvestris) 93.8%, Birch (Betula pendula) 3.3%, Fir (Pseudotsuga mensiesi) 2.3%, Oak (Quercus robur) 0.6%	95	9.8	786	25	2.0
Vielsalm (Belgium)	Beech (Fagus sylvatica) 61,7%, Fir (Pseudotsuga menziesii) 20.7%, Spruce (Picea abies) 3.2%, Pine (Pinus sylvestris) 2.7%, Fir (Abies alba) 11.7%,	65	7.5	1000	450	5.1
Le Bray (France)	Pine (Pinus pinaster) 100%	34	13.2	900	62	2.9
Tuczno (Poland)	Pine (Pinus sylvestris) 99%, Birch (Betula pendula) 1%	54	7.6	570	170	1.1-1.2

LAI versus radiation

The mutual relation between the LAI value measured by means of HP and the amount of radiation reaching both the surface of the canopy and the forest under-story has been presented in Figure 5. The canopy openness (CO) is the percentage of open sky seen from beneath the forest canopy in relation to a bigger picture. CO values in the examined tree stand varied in the range from 23.87% to 32.59% in 2009 across the measurement points. Moreover, the analyzed CO parameter is strongly influenced by the amount of light under the tree canopy. The minimum and maximum daily values of PPFD under tree canopy were 9.33 µmol m^{-2} day^{-1} and 13.38 µmol m^{-2} day^{-1}, respectively. Furthermore, the mean values of presented parameters in Tuczno forest stand were 28.71% and 11.32 µmol m^{-2} day^{-1}. The proper application of HP requires specific weather conditions (the overcast cloud cover). Therefore, the time available for taking all HP measurements is relatively short. Taking into consideration the above facts, the amount of total radiation (direct and diffuse) reaching the canopy surface in Tuczno forest is of a constant value.

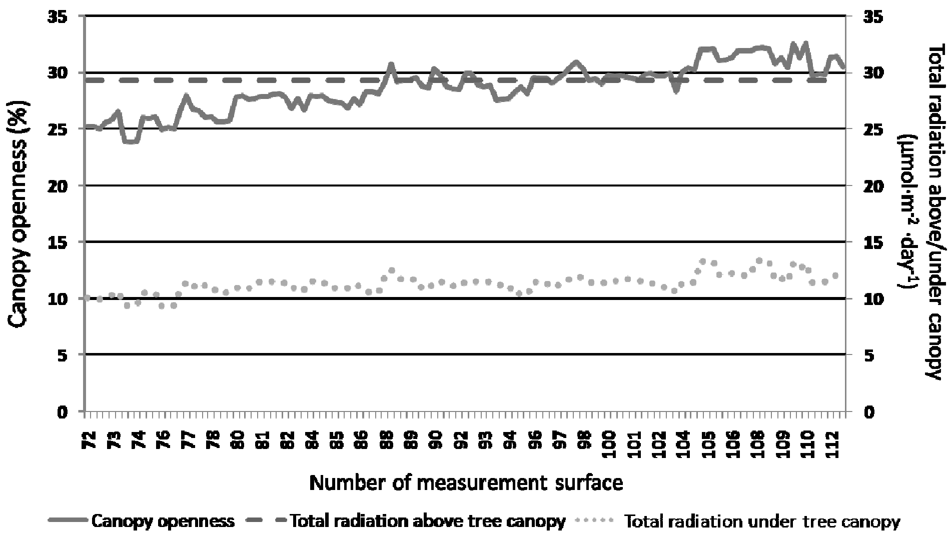


Fig. 5. The results of HP analyzes for the examined Tuczno forest stand in 2009

Laser scanning and traditional standing biomass measurements

The traditional standing biomass measurements were carried out on 369 trees in the 100-m ray from the EC measurement tower. The obtained results indicated that large timber resources (LTR) reach the values of 361 m^3 ha^{-1} (Tab. 3.). The obtained values are significantly higher than the data collected during the forest inventory which took place in 2005. This situation can be explained by the adjournment of maintenance cutting (as a result of which 20-25% of trees were supposed to be cut down). The LTR values according to the report of the inventory were estimated in the range of 273 to 291 m^3 ha^{-1} (depending on the age of trees on the measurement surface). These values in turn, are slightly higher than the average ones estimated at 260 m^3 ha^{-1} (for tree age of 50 to 57 years) for a pine forest stand, according to the National Forest Monitoring Services in Poland. The data presented above were collected in 1996.

Table. 3. The trees and forest stand characteristics in the nearest surrounding of the EC measurement tower in Tuczno site

Parameters	Trees	Canopy	Measurement surface
Number of measurement surface	32	32	32
Number of examined trees	369	89	369
Mean tree diameter D (cm)	26.5		
Mean tree height H (m)	23.2		
Mean tree volume V (m^3)	0.6265		
Mean canopy height (m)		7.8	
Mean height of steam without branches (m)		15.6	
Large timber resources (LTR) V/ha (m^3)			361.2

During the forest inventory work conducted in 2005 timber resources were estimated to amount 238 $m^3 ha^{-1}$. The total forest area in Tuczno Forest District is 22 258 ha, and pine forest stands prevail (occupying about 83.2% of the total area). The average age of a pine stand in Tuczno is 51 years (Forest Management Plan 2005).

DISCUSSION

On the basis of the results of the detailed characteristics of Tuczno pine forest stand presented above, the following conclusions can be adopted. The LAI values for the examined forest stand, which were estimated to amount from 1.1 to 1.2, are significantly lower than the data presented in the world literature. Especially rich data base regarding various forest stands characteristics can be found in the framework of CARBOEUROPE-IP project data base (Valentini *et al.* 2000, 2003). The differences between Tuczno and the sites across Europe can be partly explained by such factors as:

- the occurrence of specific conditions for HP application, both meteorological and methodological,
- differences in the conditions of the measurement site (latitude, air temperature, precipitation, the growing season length),
- the individual forest stand characteristics (tree age, height, canopy openness etc.).

The HP and its application is strictly related to the cloud cover at the time of measurement. The proper measurement requires the overcast state of the sky. If the sun disc is hidden behind the clouds application of HP is also possible. In the case when the sun disc is visible (it is not possible to conduct the research if the sun disc is hidden behind tree stems) it is extremely important to apply relevant correction factors (related to the sun location above the horizon) during the analyzes of the photographs (Bolibok 2010). Presented problems described in details Gonsamo and Pellikka 2008. The unslope /downslope site surface can disturb the obtained results (forest canopy can appear denser with only few gaps, on the other hand canopy can appear lighter with less foliar elements). Taking into consideration the fact, that the HP application in Polish conditions is extremely rare, the obtained results should be compared with the data received from LAI-2000 PCA device.

According to the presented data the relation between CO and the amount of light under the tree canopy, can be found. The maximum and minimum values of CO parameter result from the higher and lower values of the light which reaches the forest surface. Moreover, the leaf development state, amount of radiation (direct and diffused) jointly with the growing season length can determine the values of CO. Furthermore, the global trend in climate change also influenced the weather conditions at measurement sites.

The TLS and traditional biomass measurements taken simultaneously in year 2009 can provide detailed information about LTR and Tuczno forest stand characteristics (the tree height, death breast diameter, volume etc.). The differences in the LTR estimation coming from different sources (TLS measurement in 2009, National Forest Monitoring Services in 1996, Forest Management Scheme in 2005) are related to such factors as the year of measurements or the applied measurement technique etc. Although several factors mentioned above influenced the presented LTR results the differences are below the value of 30 m^3 ha^{-1}.

CONCLUSION

1. The Tuczno Scots Pine forest site is the first of this kind in Polish conditions. Because of this fact, the obtained results are especially important for the description and understanding of different biochemical and physiological processes in such a complicated ecosystem like forest. The LAI values measured in 2009 provide the initial data sets for further analyzes and comparisons with the data gathered in subsequent years.
2. The LTR values for the pine forest stand in the nearest EC tower surrounding are relatively high in comparison with the estimation from other forest

services. This situation can be explained by the adjournment of maintenance cutting (as a result of which 20-25% of trees were supposed to be cut down).

3. The presented datasets are the basis of the forest stand characteristics in Tuczno site. Furthermore, the above datasets in relation with meteorological conditions and GHG fluxes (from the EC tower) will be applied for the estimation of mass and energy balance between the atmosphere and the examined ecosystem. On the basis of the data obtained during TLS and EC measurements and eddy covariance technique, the estimation of carbon storage in the analyzed tree stand will be carried out.

Acknowledgements

The authors would like express their gratitude to the State Forests National Holding (SFNH) for financial support of presented studies.

REFERENCES

Anderson M.C., 1964. Studies of the woodland light climate. I. The photographic computation of light conditions. Journal of Ecology, 52, 27-41.

Bolibok L., 2010. Equipment and photo exposure in hemispherical photography in forest research. Forest Research Works, 71(1), 105-115.

Chan S.S., McCreight M.C., Walstad J.D., Spies T.A., 1986. Evaluating forest cover with computerized analysis of fisheye photographs. Forest Science, 32, 1085-1091.

Chen J.M., Govind A., Sonnentag O., Zhang Y., Barr A., Amiro B., 2006. Leaf area index measurements at Fluxnet-Canada forest sites. Agricultural and Forest Meteorology, 140, 257-268.

Clark D.B., Clark D.A., Rich P.M., Weiss S., Oberbauer S.F., 1996. Landscape-scale evaluation of understory light and canopy structure: methods and application in a neotropical lowland rain forest. Canadian Journal of Forest Research, 26, 747-757.

Englund S.R., O'Brien J.J., Clark D.B., 2000. Evaluation of digital and film hemispherical photography and spherical densiometry for measuring forest light environments. Canadian Journal of Forest Research, 30, 1999-2005.

Evans G.D., Coombe D.E., 1959. Hemispherical and woodland canopy photography and the light climate. Journal of Ecology, 47, 103-113.

Fournier R.A., Rich P.M., Landry R., 1997. Hierarchical characterization of canopy architecture for boreal forest. Journal of Geophysical Research, 102, 29445-29454.

Frazer G.W., Canham C.D., Lertzman K.P., 1999. Gap Light Analyzer (GLA), version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation. Burnaby, British Columbia: Simon Fraser University and Millbrook, NY: Institute of Ecosystem Studies.

Gower S.T., Kucharik C.J., Norman J.M., 1999. Direct and indirect estimation of leaf area index, fAPAR, and net primary production of terrestrial ecosystems. Remote Sensing and Environment, 70, 29-51.

Gonsamo A., Pellikka P., 2008. Methodology comparison for slope correction in canopy leaf area index estimation using hemispherical photography. Forest Ecology and Management, 256, 749–759.

Gonsamo A., Pellikka P., 2009. The computation of foliage clumping index using hemispherical photography. Agricultural and Forest Meteorology, 149, 1781-1787.

Hill R., 1924. A lens for whole sky photography. Quarterly Journal of the Royal Aleteorological Society, 50, 227-235.

Hyer E.J., Goetz S.J., 2004. Comparison and sensitivity analysis of instruments and radiometric methods for LAI estimation: assessments from a boreal forest site. Agricultural and Forest Meteorology 122 (3-4), 157-174.

Inoue A., Yamamoto K., Mizoue N., Kawahara Y., 2004. Effects of image quality, size and camera type on forest light environment estimates using digital hemispherical photography. Agricultural and Forest Meteorology, 126, 89-97.

Jonckheere. I, Fleck S., Nackaerts K., Muys B., Coppin P., Weiss M., Baret F., 2004. Review of methods for in situ leaf area index determination: Part I. Theories, sensors and hemispherical photography. Agricultural and Forest Meteorology, 121, 19-35.

Jonckheere I., Nackaerts K., Muys B., Coppin P., 2005. Assessment of automatic gap fraction estimation of forests from digital hemispherical photography. Agricultural and Forest Meteorology, 132, 96-114.

Kucharik, C.J., Norman, J.M., Gower, S.T., 1998a. Measurements of branch area and adjusting leaf area index indirect measurements. Agricultural and Forest Meteorology, 91, 69-88.

Kucharik, C.J., Norman, J.M., Gower, S.T., 1998b. Measurements of leaf orientation, light distribution and sunlit leaf area in a boreal aspen forest. Agricultural and Forest Meteorology, 91, 127-148.

Martens S.N., Ustin S.L., Rousseau R.A., 1993. Estimation of tree canopy leaf area index by gap fraction analysis. Forest Ecology and Management, 61, 91-108.

Mitchell P.L., Whitmore T.C., 1993. Use of hemispherical photographs in forest ecology. Calculation of absolute amount of radiation beneath the canopy. Oxford Forestry Institute, Department of Plant Sciences, University of Oxford. Occasional Papers.

Strzeliński P., 2006. Application of hemispherical photographs to research on forest ecosystems (In Polish). Annals of Geomatic, 4(2), 103-112.

Strzeliński P., Jagodziński A. 2010. The application of hemispherical photography in the evaluation of tree canopy architecture. [W:] Zawiła-Niedźwiecki T., Zasada M., (eds.). Geomatic techniques in the forest inventory – the examples of practical application. SGGW Warsaw (In Press).

Tompalski P., Kozioł K., 2008. Defining selected tree parameters using terrestrial laser scanning. Materials from Cracow Young Scientist Conference, 3, 337-346.

Tuczno Forest District Management Plan for the years 2005-2014. Office for Forest Management and Geodesy.

Valentini R., Matteucci G., Dolman A.J., Schulze E.-D., Rebmann C., Moors E.J., Granier A., Gross P., Jensen N.O., Pilegaard K., Lindroth A., Grelle A., Bernhofer C., Grünwald T., Aubinet M., Ceulemans R., Kowalski A.S., Vesala T., Rannik Ü., Berbigier P., Loustau D., Gudmundsson J., Thorgeirsson H., Ibrom A., Morgenstern K., Clement R., Moncrieff J., Montagnani L., Minerbi S., Jarvis P., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861-865.

Valentini R. 2003. Fluxes of carbon, water, and energy of European forests. Ecological studies, vol. 163, Springer Verlag Berlin Heidelberg.

Wagner S., 1994. Strahlungsschatzung in Waldern durch hemispharische Fotos. Berichte des Forschungszentrums Waldoekosysteme, 123, 1-169.

Watt A.S., 1947. Pattern and process in the plant community. Journal of Ecology, 35, 1-22.

Weiss S.B., 2000. Vertical and temporal distribution of insolation in gaps in an old-growth coniferous forest. Canadian Journal of Forest Research, 30, 1953-19-964.

Zawiła-Niedźwiecki T., Stereńczak K., Bałazy R., Wencel A., Strzeliński P., Zasada M., 2008. The use of terrestrial and airborne LIDAR technology in forest inventory. Ambiencia – Revista do Setor de Ciencias Agrarias e Ambientais. Vol. 4 – Edicao Especial, 57-68.

8. THE METHANE EMSSISION MEASUREMENTS USING RELAXED EDDY TECHNIQUE – PRELIMINARY RESULTS FROM RZECIN WETLAND

Bogdan H. Chojnicki[1], *Paweł Siedlecki*[1], *Janne Rinne*[2], *Marek Urbaniak*[1], *Radosław Juszczak*[1], *Janusz Olejnik*[1]

[1]Department of Physics, P.O. Box 64, 00014 University of Helsinki, Finland
[2]Meteorology Department, University of Life Sciences in Poznan (PULS)
ul. Piątkowska 94, 60-649 Poznań, Poland
e-mail: bogdan.chojnicki@up.poznan.pl

INTRODUCTION

Methane is considered as a one of the most important greenhouse gases since its very positive radiative forcing is observed in the Earth-Atmosphere system (IPCC 2007). The peculiar organic matter conservation causes large methane emission since these processes are take a place under very wet and anoxic peat conditions.

It is estimated that approximately 30% of terrestrial carbon is found in organic soils in the northern hemisphere (Gorham 1991). The form in which this carbon is stored largely stems from the fact that the processes of "preservation" of organic matter in wetland environments have been going on for thousands of years. The large amount of the carbon stored in the organic soils results from the fact that the organic matter is located in permafrost regions. Possible dissolution of those carbon pools as a result of the global warming will lead to the release of large amounts of this element into the atmosphere. This combined with the fact that the process will take place under the conditions of soil saturation with water will result in the huge amounts of methane released into the atmosphere (Friborg 2003).

Wetlands in Poland are also a source of methane emissions into the atmosphere, however, the values and seasonal dynamics of this processes requires detailed research.

Previous measurements in Poland were conducted occasionally and only by using the static dark chamber method (Paul 2005)

To test F_{CH4} in the scale of wide ecosystem it is necessary to use methods based on the theories of mass transport in the atmospheric boundary layer. One of the methods, frequently used at present to estimate methane emissions is the method of Relaxed Eddy Accumulation – REA (Rinne 2007).

The concept of ther REA system was developed in the Meteorology Department Pozanń University of Life Sciences, it was built and successfully applied. It can continuously perform automated measurements of CH_4 fluxes.

This article describes the construction, operation, and preliminary results of F_{CH4} field measurements carried out at the measuring station in Rzecin which has been built and maintained by the employees of the Meteorology Department at the University of Life Sciences in Poznan.

SITE DESCRIPTION

The new system was tested and applied at Rzecin Wetland site, Poland (52°45’ N latitude, 16°18’ E longitude, 54 m a.s.l.). This object is owned by Poznan University of Life Sciences and Rzecin and the measuring station has been developed, managed and serviced by the Meteorology Department scientific group. This is the first wetland station in Poland where permanent measurements of greenhouse gas exchange (CO_2, CH_4 and N_2O) have been carried out since the end of 2004.

The equipment that is installed at Rzecin site is constantly developed, however, several systems have existed there right from the beginning of the station e.g. eddy covariance (EC) system for measurements of CO_2, water and energy fluxes, solar radiation, air and soil temperature probes etc. (Chojnicki *et al*. 2007). The REA system was installed at the distance of 100 meters from the EC Tower where REA power supply was also located. It is located in the middle of the study site.
The study area is approximately of 140 ha and the local plant cover is dominated by following species: *Sphagnum sp., Dicranum sp., Carex sp., Phragmittes communis, Typha langifolia, Vaccinium oxicoccus, Drosera rotundifolia, Potentilla palustris, Ranunculus acris, Menyantes trifoliate* etc. (Wojterska et al. 2001).

The Rzecin substrate is described as a Limnic Hemic Floatic Ombric Rheic Histosol (Epidystric) in terms of the FAO 2006 classification.

The annual mean air temperature and precipitation calculated for the measurement period from 2004 to 2010 were 8.5°C and 526 mm, respectively. The floating peat carpet (50cm thick) is located in the middle of Rzecin area while the sandy bedrock based regular peat is found outside.

THEORETICAL BACKGROUND OF REA MEASURING SYSTEM FUNCTIONING

Measurements of the size and direction of mass and energy fluxes in the atmosphere can be performed by applying various methods. Eddy Covariance method (EC) is currently regarded as the best and most reliable, however, its application is particularly troublesome for the measurements of gases whose concentrations in the air are very small, e.g. methane, etc. Usage of the covariance system requires the application of a set consisting at least of an ultrasonic anemometer and a gas analyzer which performs measurements at a frequency of not less than 10 Hz. While the application of the anemometer that is sufficiently fast is not a problem (the current technical level enables building adequate equipment), the construction of a suitable rapid gas analyzer dealing with many atmospheric substances still causes a lot of technical problems.

One of the methods, which is the modification of covariance method and simultaneously allows using a slower gas analyzer is the simplified method of Relaxed Eddy Accumulation – REA. It was derived from Eddy Accumulation method (EA) (Desjardins 1972). EA is based on a simple strategy which allows avoiding the limitations associated with the speed (frequency) of measurements. It consists of collecting air samples, depending on the sign (direction) and size of wind velocity vertical component (w). When w> 0, the air is sucked into the top tank, and when w<0 the air is collected in the bottom tank. A sample size is proportional to the size of wind velocity vertical component (w). At the end of the sampling period the measurements of their concentrations in the tanks are performed (Desjardins 1977). Despite the simplicity of this method, field tests have not given satisfactory results, because it required high-precision measurements of the volumes of the collected samples. This requirement resulted from the necessity of proportionality of the sampled air volume to the size of the vertical component of wind velocity (w). In 1990, Businger and Oncley published their own version of EA method, which they called the Relaxed Eddy Accumulation (REA). In their version of the method they gave up sampling air that had volume proportional to w parameter. REA method collects the air with a constant flux rate, basing only on the sign of w (Businger & Oncley 1990). The flux determined by using of this method is described by the equation:

$$F = \beta\sigma_W \left(\overline{C}_{up} - \overline{C}_{down}\right) \tag{1}$$

where: F – net gas flux density (µmol m^{-2} s^{-1});
β – empirical coefficient (1 m^{-1});
σ_W – standard deviation of the wind velocity vertical component (m s^{-1});
$\overline{C}_{up}$ – average gas concentration in the top tank (µmol m^{-3});
$\overline{C}_{down}$ – average gas concentration in the bottom tank (µmol m^{-3}).

When the gas concentration is expressed by the mixing ratio, then the equation which is used to calculate F_{CH4} takes the following form (Pattey *et al.* 2006):

$$F = \beta\sigma_W \frac{M_s}{M_a} \overline{\rho}_a \left(\overline{S}_{up} - \overline{S}_{down}\right) \tag{2}$$

where additionally:

$\overline{S}_{up}$ – mean trace gas molar mixing ratio in updrafts (µmol mol^{-1});

$\overline{S}_{down}$ – mean trace gas molar mixing ratio in downdrafts (µmol mol^{-1});

M_s – molecular mass of the gas (g mol^{-1});

M_a – molecular mass of the dry air (g mol^{-1});

$\overline{\rho}_a$ – mean molar density of the dry air (µmol m^{-3});

This paper adopts the principle according to which the flux outgoing from the surface has a positive value and the absorbed flux a negative one.

β is an empirical coefficient, which can be determined by two different methods. The first involves the calculation of the average value of the coefficient on the basis of long-term data set from the EC system by using a transformed equation (1), e.g. on the basis of air temperature:

$$\beta = \frac{\overline{w'T'}}{\sigma_W\left(\overline{T}_{up} - \overline{T}_{down}\right)} \tag{3}$$

where: $\overline{w'T'}$ – vertical wind component and air temperature covariance (K·m·s^{-1})

$\overline{T}_{up}$ – mean air temperatures in updrafts (K);

$\overline{T}_{down}$ – mean air temperatures in downdrafts (K).

The second method consists of determining β coefficient using one of two following equations. First (Businger and Oncley 1990):

$$\beta \cong \beta_0 \exp\left(\frac{-0.75|w_0|}{\sigma_w}\right) \tag{4}$$

where: $\beta_0 = \beta(|w_0| = 0) \cong 0.6$

$|w_0|$ – threshold velocity for up and down sampling (usually between 0 and σ_W).

Second equation (Pattey *et. al*. 1993):

$$\beta = \beta_0\left(1 - 0.437\left(1 - \exp\left(-1.958\, w_0 / \sigma_w\right)\right)\right) \tag{5}$$

The theoretical value of β coefficient ranges from 0.62 to 0.627, however, determined on the basis of raw data from the EC system this ratio is lower and ranges from 0.56 to 0.58 (Baker 1992, Pattey *et al*., 1993, Beverland *et al*., 1996, Katul *et al*. 1996). It was also proved that the use of β coefficient determined on the basis of apparent heat fluxes for the calculation of CO_2, H_2O and ozone fluxes does not cause an error greater than 4%, while the use of constant β coefficient of 0.56 should not cause an error greater than 1% (Baldocchi 2005). There was also no evidence of a relationship between β coefficient and the stability parameter (z / L) (Katul *et al*. 1996).

To increase the differences between the concentrations of the tested gases in the tanks, the threshold value was established which was used to create a dead band in previous studies. While the samples are collected by REA system they are placed in two reservoirs, an upper and a lower one. The samples go to the lower reservoir, when $w < -w_{db}$ (where w_{db} is a threshold value), and the samples go to the upper reservoir when $w > w_{db}$. In contrast, when $-w_{db} < w < w_{db}$ – inside the dead band – samples are not collected in any of the tanks. As a result of that the tanks get only samples of the eddies with the vertical velocity sufficient to exceed the applied threshold value. In order to avoid the situation in which the increase in the concentration differences between the samples would cause the overstatement of the calculated flux value, β coefficient has to be reduced (Businger and Oncley 1990, Pattey et al. 1993).

During further research a relationship was found between the dead band size and the difference of gas concentrations between the samples. The larger the dead band, the higher was the difference between the concentrations of gas in the tanks. The measure of a dead band range is a standard deviation from the vertical component of wind velocity (STD(w)). The biggest differences in concentrations are obtained for STD(w) from 0.5 to 0.6 $m \cdot s^{-1}$ and further increase of STD(w) does not give better results. Basing on the theory described above REA measurement system was built in the Meteorology Department.

CONSTRUCTION AND OPERATION OF REA MEASURING SYSTEM BUILT IN METEOROLOGY DEPARTMENT OF PULS

Classic measurement system based on REA methodology consists of the following parts (Baldocchi 2005):

1. anemometer,
2. two reservoirs,
3. valve system (air directing),
4. pump,
5. control module.

Its operation consists in collecting air samples in two containers for a specified period e.g. 30 minutes. After this time the collected air is passed, usually manually, to the analyzer where it is subjected to further analysis. The system constructed in such a way unfortunately does not operate continuously, it requires breaks in the measurements and the active involvement of the research staff during the measurements.

The system developed at the Department of Meteorology, the University of Life Sciences in Poznań has been designed so that it can operate autonomously in a continuous way. It has been equipped with two sets of tanks and a gas analyzer. Thus, when in the one of the sets the air samples are collected, at the same time, the air from the second set is pumped into the analyzer. Adding the second set of tanks complicated the whole system and in particular the valve system. A single tank consists of a hermetic container in which a bag made of a not reactive material – tedlar is mounted. Air samples are collected in bags and their filling and emptying is done through the changes of pressure in the containers (Fig. 1).

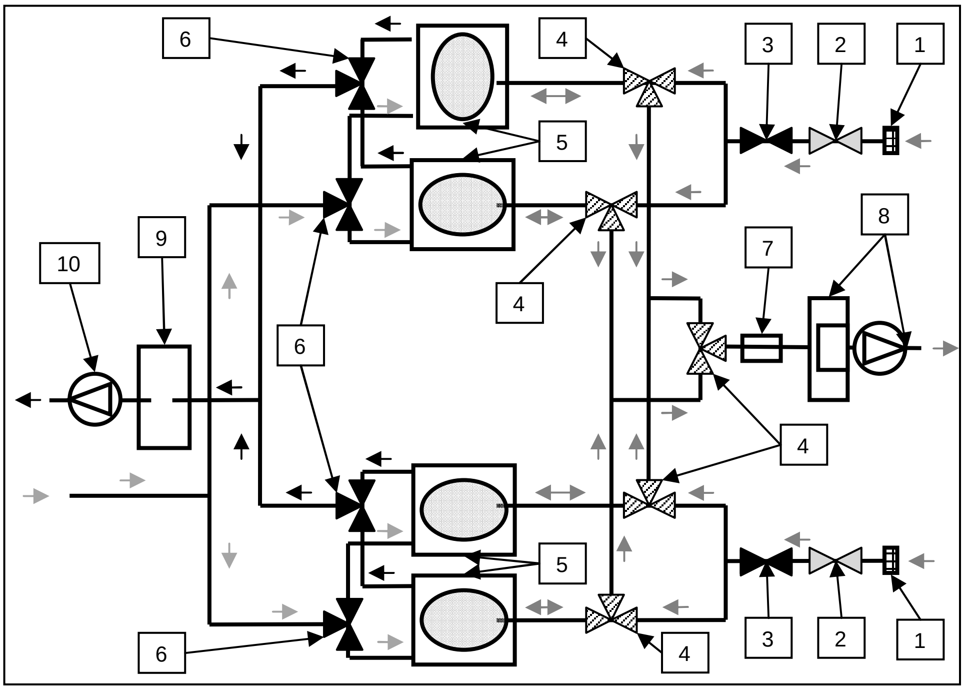


Fig. 1. The Relaxed Eddy Accumulation construction scheme where the following elements are found: 1. filter, 2. needle valve, 3. 2/2 valve (PTFE made), 4. 3/2 valve (PTFE made), 5. gas sample container and bag (ellipse), 6. 3/2 valve (Brass made), 7. flow meter, 8. gas analyzer with pump, 9. Buffer tank, 10. pump; black arrow – underpressure, light gray arrow – overpressure, dark gray arrow – sampled air

The equipment is controlled by an automatic control system, which apart from steering the valves, processes and stores the measurement data. The system stores in its memory not only the concentration values in the tanks, but also the fundamental values of the statistical characteristics of wind velocity and the system diagnostic data. In this way, after the installation of the system, it does not require intense supervision and the service comes down to data transfer from time to time.

MATERIAL AND METHODS

The results of the observations presented in this paper come from the period from October 2nd to 7th, 2009. The average air temperature during this period was 9.4°C while the observed extreme values of air temperature were 16.0°C maximum and 1.3°C minimum respectively.

The weather recorded during the measurements was cloudy with periodic rain. Analysis of the data obtained from the measurements conducted by REA system at Rzecin peat bog, consisted of several steps.

At the beginning the series of measurements was divided into 30-minute periods and for each of them STD(w) values and the average methane concentration in the air samples from the lower and upper reservoirs were calculated.
Concentrations were corrected for temperature and pressure in the gas analyzer measurement chamber - for this purpose the following formula was used:

$$\rho_{CH_4}^{corr} = \frac{P \cdot M}{R \cdot T \cdot r_{CH_4}} \tag{6}$$

where: $\rho_{CH_4}^{corr}$ – corrected methane concentration (μg m^{-3});
P – air pressure (Pa);
M – molar mass (g mol^{-1});
R – molar gas constant (J mol^{-1} K^{-1});
T – air temperature (K);
r_{CH_4} – methane mixing ratio (μmol mol^{-1}).

After the correction of concentrations in the reservoirs, the F_{CH4} fluxes were calculated using formula 1 with β coefficient value adopted arbitrarily as equal to 0.44. This value is different from values presented in literature, however it was assessed within β coefficient values studies realized using a EC data set obtained at Rzecin Wetland before (Siedlecki 2007).

Due to the similarity of theoretical assumptions of REA and EC methods they have the same limitations. This is particularly noticeable in the conditions of high stability in the atmospheric boundary layer. The REA and EC measurements are in such conditions impossible to perform due to poor air mixing (Aurela 2005, Black *et al*. 1996, 2000, Urbaniak 2006). This was one of the main reasons for discontinuities which appeared in the data series from the measurement period.

RESULTS

The application of REA system allowed estimating the values of net methane fluxes observed above the surface of the peat bog. The results were compared with the values of average air temperature measured at the height of 2 meters above the ground (ta2m) (Fig. 2) and the average temperature values measured in the peat at the depth of 10 centimeters below the surface (ts10cm) (Fig. 3). The average value of FCH4 during this period was 401.9 µg m^{-2} h^{-1}, the minimum flux was – 270.2 µg m^{-2} $h^{-1}$and the maximum was 1192.1 µg m^{-2} h^{-1}. Measuring period was far too short to draw conclusions as to the value of seasonal methane emissions from peatlands in Rzecin, but the momentary FCH4 values and high variability in time of FCH4 values are comparable with those presented in the literature (Rinne 2007). Daily periodicity of emissions is not clear which has also been observed in other peatlands. This low correlation is clearly visible at both figures (Fig. 2 and Fig. 3) since the net methane flux density is dependent on more factors than temperature e.g. substrate composition, soil water level.

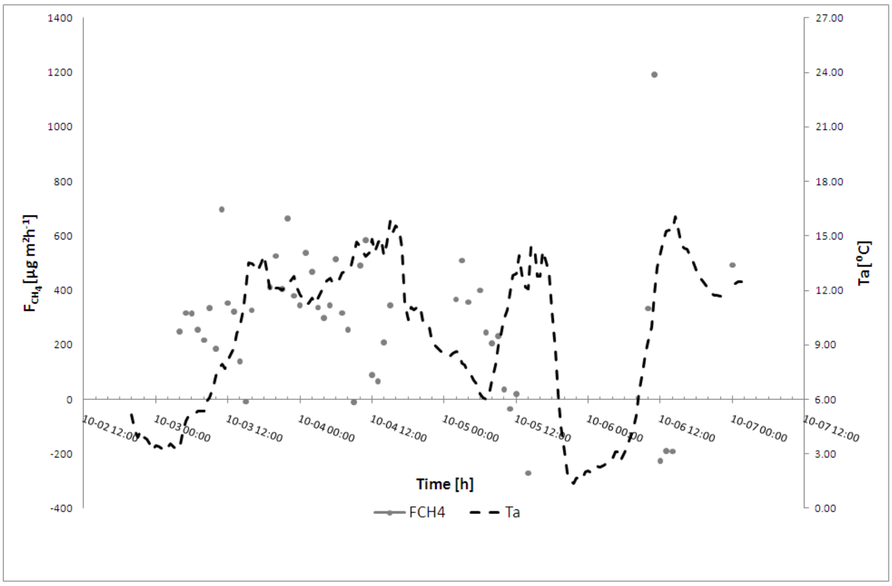


Fig. 2. The course of the 30-minute average CH4 net fluxes F_{CH4} (µg m^{-2} h^{-1}) and the air temperatures at the height of 2 meters above the ground ta2m (ºC)

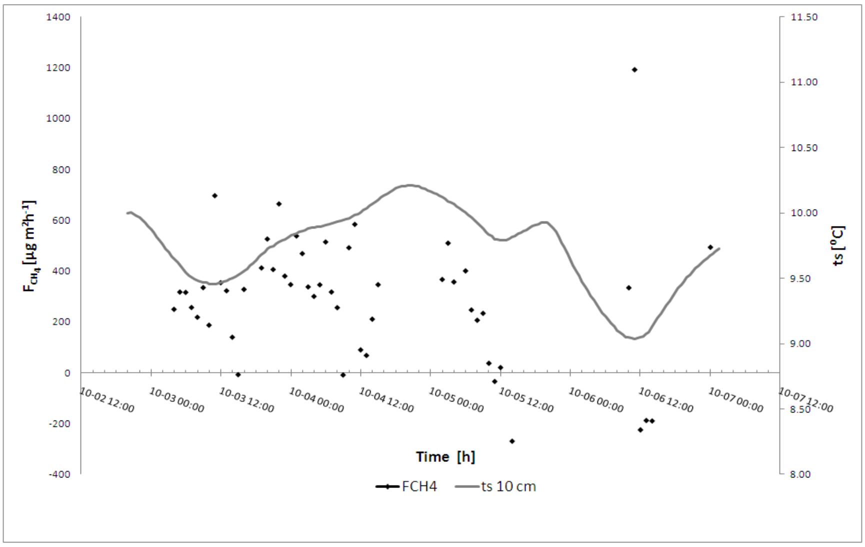


Fig. 3. The course of the 30-minute average CH4 net fluxes F_{CH4} (µg m^{-2} h^{-1}) and the soil temperatures at the depth of 10 centimeters below the surface ts10cm (ºC)

DISCUSSION AND CONCLUSIONS

Preliminary measurement results indicate that in the peat in Rzecin the observed methane emission is on the level of 401.9 µg m^{-2} h^{-1} in the cool period of the year. The values of the observed fluxes show high variability in time. One can not see a clear cyclical patterns of F_{CH4} throughout the day. It can be assumed that the process of methane production in the wetlands should be correlated with the temperature of subsurface soil layer. This is due to the relationship between this temperature and microbiological activity, which is the direct cause of CH_4 emission by such environments. Our results are similar to those encountered in literature, suggesting that CH_4 release from the depths of the bog profile to the atmosphere is a random phenomenon, temporarily modifying the value of the flux.

The results presented in this study indicate the usefulness of the new REA system for measuring methane emissions. Newly developed system was designed so that the automatic measurements are possible to be conducted using REA technique and the staff supervision is limited to minimum. This will allow for continuous measurements of methane flux, which, in the light of the presented results, will enable estimating the emissions of this gas into the atmosphere more accurately. In consequence it will correct the data obtained from the chamber measurements, made at much longer time intervals. An additional advantage of automatic REA system, which consists in a negligible interference in the structure of the wetland area, will eliminate the impact of movements and pressure of the observer feet on the momentary methane flux values.

Acknowledgements

The presented studies has been supported by the following European Community's Sixth Framework Programme projects: a GREENFLUX-TOK contract no. MTKD-CT-2006-042445 and NITROEUROPE-IP contract no. GOCE-CT-2006-017841

REFERENCES

Aurela M., (2005). Carbon dioxide exchange in subarctic ecosystems measured by a micrometeorological technique. Finnish Meteorological Institute Contributions, No. 51.

Baker J. M., 2000. Conditional sampling revisited. Agricultural and Forest Meteorology 104 (2000) 59–65

Baldocchi D., 2005. ESPM 228, Advanced Topic in Biometeorology and Micrometeorology, Lecture, 5 Eddy Accumulation Techniques and Alternative Micrometeorological Flux Measurement Methods, Ecosystem Science Division, Department of Environmental Science, Policy and Management, 345 Hilgard Hall, University of California , Berkeley, CA 94720, 1-4, 6-9.

Beverland I. J., ONeill D. H., Scott S. L., Moncrieff J. B., 1996. Construction and operation of flux measurement systems using the conditional sampling technique. Atmospheric Environment, Vol. 30, No. 18, 3209-3220.

Beverland I. J., Moncrieff J. B., ONeill D. H., Hargreaves K. J., Milnez R., 1996. Measurement of methane and carbon dioxide fluxes from peatland ecosystems by the conditional-sampling technique Q. J. R. Mereorol. Soc., 122, 819-838.

Black T.A., Chen W.J., Barr A.G., Arain M.A., Chen Z., Nesic Z., Hogg E.H., Neumann H.H., Yang P.C., 2000. Increased carbon sequestration by a boreal deciduous forest in year with a warm spring. Geophys. Res. Lett., 27, 1271-1274.

Black T.A., den Hartog G., Neumann H.H., Blanken P.D., Yang P.C., Russell C., Nesic Z., Lee X., Chen S.G., Staebler R., Novak M.D., 1996. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest, Global Change Biology, 2, 101-111.

Bowling D.R., Delany A. C., Turnipseed A. A., Baldocchi D., Monson R. K., 1998. Modification of the relaxed eddy accumulation technique to maximize measured scalar mixing ratio differences in updrafts and downdrafts, Journal of Geophysical Research, Vol. 104, No. D8, Pages 9121-9133, April 27, 1999.

Bowling D. R., Turnipseed A. A., Delany A. C., Baldocchi D. D., Greenberg J. P., Monson R. K., 1998. The use of relaxed eddy accumulation to measure biosphere-atmosphere exchange of isoprene and other biological trace gases. Oecologia, 116, 306-315.

Brut A., Legain D., Durand P., Laville P., 2004. A Relaxed Eddy Accumulator for Surface Flux Measurements on Ground-Based Platforms and Aboard Research Vessel. Journal of Atmospheric and Oceanic Technology, 21, 411-427.

Businger J.A., Oncley S.P., 1990. Flux measurement with conditional sampling. National Center for Atmospheric Research, Boulder Colorado, 349-352.

Chojnicki B. H., Urbaniak M., Leśny J., Juszczak R., Olejnik J., 2007. The modern techniques applied for mass and heat exchange between ecosystems and atmosphere measurements. Przegląd Naukowy Inżynieria i Kształtowanie Środowiska, 1(39), 91-97.

Desjardins R.L., 1972. A study of carbon dioxide and sensible heat fluxes using the eddy correlation technique, Ph.D. dissertation, Cornell University.

Desjardins R. L., 1977. Description and Evaluation of a Sensible Heat Detector. Boundary-Layer Meteorology, 11, 147-154

Friborg T., Soegaard H., Christensen T.R., Lloyd C.R., Panikov N.S., 2003. Siberian wetlands: Where a sink is a source. Geophysical Research Letters, 30 (21), 2129,

Gaman A., Rannik U., Aalto P., Pohja T., Shvola E., Kumala M., Vesala T., 2004. Relaxed Eddy Accumulation System for Size-Resolved Aerosol Particle Flux Measurements. Journal of Atmospheric and Oceanic Technology, 21, 933-943.

Gorham E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climate warming. Ecological Applications, 1(2), 182-195.

Katul G.G., Finkelstein P.L., Clarke J.F., Ellestad T.G., 1996. An Investigation of the Conditional Sampling Method Used to Estimate Fluxes of Active, Reactive, and Passive Scalars. Journal of Applied Meteorology, 35, 1835-1845.

Pattey E., Desjardings R.L., Rochette P., 1993. Accuracy of the relaxed eddy-accumulation technique, evaluated using CO2 flux measurements, Boundary Layer Meteorology, 66.

Pattey E., Strachan I.B, Desjardins R.L., Edwards G.C., Dowa D., MacPherson J.I., 2006. Application of a tunable diode laser to the measurement of CH4 and N2O fluxes from field to landscape scale using several micrometeorological techniques. Agricultural and Forest Meteorology, 136, 222-236.

Paul M., 2005. Methane efflux dependency of substrate temperature at Rzecin wetland. MSc thesis. Agric. Univ. in Poznań (in Polish)

Rinne J., Riutta T., Pihlatie M., Aurela M., Haapanala S., Tuovinen J., Tuittila E., Vesala T., 2007. Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. Tellus, 59B, 449-457.

Siedlecki P., 2007. The wind speed vertical component deadband size impact on measured carbon dioxide concentrations differences. MSc thesis. Agric. Univ. in Poznań (in Polish)

Wojterska M., Stachanowicz W., Melosik I., 2001. Flora and vegetation of Recińskie Lake near Wronki town peatland (in) Wojterska M., ed. Szata roślinna Wielkopolski i Pojezierza Południowo-pomorskiego. Przewodnik sesji terenowych 52. Zjazdu Polskiego Towarzystwa Botanicznego, 24-28 września 2001. Oddział Poznański PTB, Bogucki Wyd. Nauk. Poznań, 211-219. (in Polish)

Zemmelink H.J., Gieskes W.W.C., Klaassen W., de Groot H.W., de Baar H.J.W., Dacey J.W.H., Hintsa E.J., McGillis W.R., 2002. Simultaneous use of relaxed eddy accumulation and gradient flux techniques for the measurement of sea-to-air exchange of dimethyl sulphide. Atmospheric Environment, 36, 5709-5717.

9. NIGHT-TIME CO_2 CHAMBER MEASUREMENTS IN PEATLAND ECOSYSTEM IN POLAND

Radosław Juszczak[1], *Manuel Acosta*[1], *Maria Michalak*[1], *Bogdan H. Chojniki*[1], *Marek Urbaniak*[1], *Matthias Drösler*[2], *Jürgen Augustin*[3], *Janusz Olejnik*[1]

[1]Meteorology Department, Poznan University of Life Sciences, ul. Piątkowska 94, 60-649 Poznań, Poland
e-mail: radjusz@up.poznan.pl
[2] Lehrstuhl für Vegetationsökologie Technische Universität München, Am Hochanger 6, D-85350 Freising, Germany
[3]Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, D-15374 Müncheberg, Germany

INTRODUCTION

Peatlands are peculiar ecosystems accumulating organic matter as a consequence of the imbalance between net primary production and decomposition, with decomposition being slower than net primary production. Such imbalance makes peatlands effective sinks for atmospheric C, thus, these ecosystems are estimated to store about one-third of the global soil C pool (Gorham 1991, Clymo *et al.* 1998). The peatland plant communities play an important role in ecosystem carbon dynamics and storage, with every species possessing a unique functional phenotype (Gajewski *et al*. 2001). Although, a considerable amount of work has been done to assess the impact of CO_2 on terrestrial ecosystems (mainly grassland and forests ecosystems), there is still a paucity of information regarding the responses of peatlands. Moreover, the climate change will alter terrestrial ecosystem (IPCC 2007) mainly by changes in soil temperature and soil moisture, both of which having a strong impact on CO_2 fluxes. Peatlands have been considered as a long term net sink of carbon, but their future ability to store C seems to be unclear. Decreasing groundwater table caused by warmer and drier weather will lead to aerobic conditions in the peat substrate. As a consequence, the enhanced microbial decomposition of organic matter determined by aerobic conditions can modify peatland carbon balance to become the long term net source of CO_2 (Brown 1998, Alm *et al*. 1999, Aurela *et al*. 2001). Therefore, all studies of peatland greenhouse gases exchange processes are very important to better understand the importance of wetland ecosystems in the global C cycle.

Carbon dioxide flux is quantified by means of several different approaches. The techniques in use include micrometeorological methods such as eddy covariance (Aubinet *et al*. 2000, Barford *et al*. 2001, Baldocchi 2003, Lafleur *et al*.

2003, Chojnicki *et al*. 2007), aircraft measurements and direct measurements using various types of chambers (eg. Livingston and Hutchinson 1995, Pumpannen *et al*. 2004). Chamber types include static, air-tight chambers (non steady state, non-flow through) and dynamic, flow-through chambers (Livingston and Hutchinson 1995). Chambers can be operated manually, or be programmed to make measurements automatically. The methods of measurements involving closed chambers, that follow CO_2 mixing ratio changes in an isolated headspace above the surface, are perhaps the most common techniques for quantifying peatland CO_2 exchange (Drösler 2005, Livingston *et al*. 2006, Chojnicki *et al*. 2010).

Generally, the chamber method can be used for the direct measurements of ecosystem respiration (eg. Bekku *et al*. 1997, Acosta *et al*. 2004, Pumpannen *et al*. 2004). This method is not affected by CO_2 advection. Nevertheless, manual chambers require greater time, physical labor and logistics, which makes this technique more difficult especially during night-time and winter measurements. Therefore, mainly day-time manual chamber measurements are usually used to model and evaluate the ecosystem CO_2 exchange. However, the underestimation of nocturnal CO_2 efflux measured by the eddy covariance method under calm, stable conditions remains an unsolved problem at many flux observation sites (Goulden *at al.* 1996, Lafleur 1999, Baldocchi 2003). Due to this, the night time chamber measurements of CO_2 fluxes are extremely required and helpful for the estimation of nocturnal CO_2 efflux. Measurements carried out by closed chamber technique were often used to quantify the CO_2 flux underestimation during the application of eddy covariance method (Zamolodchikov *et al.* 2003, Reth *et al.* 2005, van Gorsel *et al*. 2007). However, Hutchinson *et al.* (2000) and Schnider *et al.* (2009) proved that the results of chamber measurements depend also on the near surface mixing conditions and during night-time low turbulence conditions, which can lead to overestimation of the CO_2 efflux measured by chamber techniques.

In this study, we measured the CO_2 efflux during night-time conditions at four sites (different vegetation communities and water table) over one-year period in a peatland ecosystem located in Poland, using a dynamic chamber method. The use of the chamber method allowed us to study both, spatial and temporal variations in CO_2 efflux. Our aims were: *(1)* to characterize the CO_2 efflux by vegetation communities along the peatland area; *(2)* to quantify the CO_2 efflux over night-time conditions; *(3)* to determine the influence of temperature on CO_2 efflux and *(4)* to investigate the temporal variation in CO_2 efflux.

MATERIALS AND METHODS

Study Site

The study was carried out at Rzecin peatland site, Poland (52^{o}45’ N latitude, 16^{o}18’ E longitude, 54 m a.s.l.). Rzecin site (POLWET) is owned by Poznan University of Life Sciences and is managed by the Meteorology Department, Faculty of Land Reclamation and Environmental Engineering. This is the first wetland station in Poland, where continuous measurements of greenhouse gases (GHG) exchange (CO_2, CH_4 and N_2O) are carried out (since January 2004). The POLWET site was the core site of the CARBOEUROPE-IP (FP6) project and still is the main site within NITROEUROPE-IP (FP6). The station is well equipped with high level instruments such as eddy covariance system for the measurements of CO_2, H_2O and energy fluxes (Chojnicki *et al*. 2007), solar radiation, air and soil temperature probes etc. Additionally, manual chamber techniques are used for the measurements of GHG fluxes.

The area of the studied peatland is about 140 ha. This is an ombrotrophic and mostly oligothrophic bog surrounded by a pine forest of Notecka Primeval Forest. On the edge of the wetland (close to forest) there are located individual farms/buildings of Rzecin village, but the anthropogenic pressure brought on the wetland ecosystem is relatively small. Due to this Rzecin wetland is classified as semi-natural. In the middle of the peatland there is a 50-cm thick floating carpet of peat-substrate overgrown mostly by mosses. Vegetation is dominated by following plant species: *Sphagnum sp., Dicranum sp., Carex sp., Phragmittes communis, Typha langifolia, Vaccinium oxicoccus, Drosera rotundifolia, Potentilla palustris, Ranunculus acris, Menyantes trifoliate* (Wojterska *et al*. 2001). The soil substrate is a Limnic Hemic Floatic Ombric Rheic Histosol (Epidystric), according to FAO 2006 classification. The average annual air temperature and the sum of precipitation are 8.5°C and 526 mm, respectively.

Experimental setup

Night-time CO_2 effluxes were measured once a month from July 2008 till the end of May 2009 by means of a closed dynamic chamber approach. During each campaign, the measurements started in the late evening (just before sunset) and were continued till the sunrise of the following day. 4 different microsite types were established in 2007. The first microsite (S1) is dominated by *Caricetum elatae* plant communities, the second (S2) by *Calamagrostietum neglectae*, the third (S3) by *Menyantho-Sphagnetum teretis* and the fourth (S4) by *Sphagno apiculati-Caricetum rostratae* (Wojterska *et al*. 2001). Each microsite consists of three plots. At each measurement plot, permanent collars made from PCV (75 cm x 75 cm) were installed in 2007. The insertion depth of the collar was about

20 cm. Elevated boardwalks were constructed at each site to prevent the disturbance of the plant cover and peat during the measurements.

At each microsite, soil temperature was measured at the depths of 2 cm, 5 cm and 10 cm, with the sampling frequency of 5 seconds (T-109, Campbell Sci., USA). Soil thermometers were installed close to the middle plot of each site. Additionally, air temperature was measured with the same frequency at the hight of ca. 35 cm. The air thermometers (T-107, Campbell Sci., USA) were installed on the chamber wall in order to measure both inside and outside temperature values. All sensors were connected to a data-logger (CR 1000, Campbell Scientific, USA) which recorded values at 5-second intervals. Moreover, air temperature at the height of 2 m and soil temperature profile at different depths (2, 4, 6, 10, 20, 30 and 50 cm) were measured (together with other meteorological variables) at the eddy covariance tower during the whole year.

The groundwater level was measured during the daily campaigns that preceded the night-time chamber measurements. The measurements were carried out manually at 3 tubes preinstalled in July 2008 close to the edge of each collar. Precipitation was measured automatically by a rain gauge (RG2-M, Onset, USA).

CO_2 fluxes measurements

A dynamic chamber system (a non-steady-state through-flow chamber system according to Livingston and Hutchinson 1995) was applied to measure the night-time CO_2 fluxes. The chamber (77 cm x 77 cm x 50 cm) has been made from white PCV, with wall thickness of 3 mm and has a volume of 0.3 m^3. The applied dark chamber system was originally proposed and devised by Drösler (2005). The chamber has been equipped with two fans (Sunon, MagLev, Taiwan) with the flow of about $1ms^{-1}$, to mix the air during measurements, and two thermometers (T-107, Campbell Scientific, USA) installed in order to measure the inside and outside air temperature. Pressure changes during measurements have been minimized by the vent tube Ø 6 mm and 40 cm long which has been inserted downwards into one of the chamber walls. During the measurements, the chamber was put on the preinstalled collars and fixed to them by two elastic belts connecting the top of the chamber and the base of the frame. The tightness of the chamber during measurements was assured by a rubbery gasket installed on the chamber lower edge (according to the system developed by Drösler (2005)). The CO_2 concentration changes were measured using a CO_2 infrared gas analyzer (LI-820, Licor, USA) with the flow rate of 600 ml min^{-1}. The readings were recorded with 5-second intervals over 150 seconds in summer and up to 240 seconds in winter. Data were recorded by the data logger (CR-1000, Campbell Sci., USA) installed in a portable control box. The logger was connected to a palmtop, thus all measured parameters and system performance were easily checked during measurements. Additionally, in order to identify each of the measurement plots, the chamber was equipped with a bar code scanner (the bar code label on the metal stick was preinstalled at each plot before measurements).

The number of night-time measurements of CO_2 effluxes at each site was different for each campaign. In total, there were 642 single measurements carried out within all sites, when the data received allowed for flux calculations and $r^2>0.8$. Different number of measurements conducted at each site was dependent mostly on the peat temperature changes over night. When the temperature changes were more essential, more measurements were conducted. During night-time summer campaigns, 7 repetitions throughout all of the 12 plots were carried out. While, during the winter night-time campaigns, when the measured peat temperature was close to zero Celsius degrees and did not change very much, there were only few (3 to 4) measurements at each site (always with three replicates), as the expected and measured changes of CO_2 fluxes over night were very small.

CO_2 fluxes calculations

The CO_2 fluxes were calculated on the basis of CO_2 concentration changes in the chamber headspace over time. The total chamber headspace for fluxes calculation was calculated as the sum of the chamber volume and the volume of an individual collar. The linear approach was applied for flux calculations by fitting the linear regression function, which determines the average rate of concentration changes over closure time. The collected time series were validated in terms of temporal linearity of CO_2 concentration. The correlation coefficient (r^2) were calculated for each series and if $r^2 > 0.8$, then CO_2 flux rate (F_{CO_2}) was calculated and used for modeling. The Münchmeyer (2001) equation was applied for CO_2 fluxes calculation:

$$F_{CO_2}[\mu g \cdot CO_2 - C \cdot m^{-2} \cdot h^{-1}] = \frac{M[g \cdot mol^{-1}] \cdot P[Pa] \cdot V[m^3] \cdot \delta v[ppm(v)] \cdot f_1}{R[m^3 \cdot Pa \cdot K^{-1} \cdot mol^{-1}] \cdot T[K] \cdot t[h] \cdot A[m^2]}$$

where:

F_{CO_2} – CO_2 flux density (µg CO_2-C m^{-2} h^{-1}),
M – molar mass (g mol^{-1}),
P – atmospheric pressure (Pa),
δv – CO_2 concentration changes in chamber over closure time (ppm(v)/h),
V – total volume of chamber and collar (m^3),
R – gas constant (m^3 Pa K^{-1} mol^{-1}),
T – temperature in chamber (K),
t – closure time (h),
A – chamber area (m^2),
f_1 – factor used for calculation of C atoms into CO_2 (12 g/44 g).

Modeling of CO_2 fluxes/Ecosystem Respiration (R_{eco})

The nighttime CO_2 fluxes were modeled on the basis of fluxes measured at 30-min intervals for the period of 1.06.2008 till 31.05.2009. The modeling was carried out only for the night hours for each month separately. Night length devoted for modeling was defined basing on the average length of nights (between sunset and sunrise) in each month (the hours of sunrise and sunset of the 1st, middle and last day of the month were taken for calculations). A nighttime CO_2 fluxes are per definition equal to nighttime CO_2 ecosystem respiration (R_{eco}), which is defined as a sum of soil respiration (heterotrophic respiration + autotrophic respiration of roots) and aboveground autotrophic respiration of plants tissues.

The nighttime R_{eco} was empirically modeled on the basis of the first-order exponential regression model of Lloyd and Taylor (1994). The parameters R_{ref} and E_o of the equation used for modeling were defined separately for each of the campaign based on regression analyses of the measured fluxes and different temperatures (air temperature, soil temperature at 2 cm, 5 cm and 10 cm depth) on the basis of abovementioned exponential equation of Lloyed and Taylor (1994). Parameters received for the best fitted correlations between air/peat temperatures and measured CO_2 effluxes were then used for modeling. The equation used for modeling (Lloyed and Taylor 1994):

$$R_{eco} = R_{ref}\, e^{\,Eo\,(1/(Tref - T_0) - 1/(\,Tsoil - T_0))}$$

where:

- R_{eco} – ecosystem respiration (CO_2-C mg m^{-2} h^{-1}),
- R_{ref} – respiration at the reference temperature (CO_2-C mg m^{-2} h^{-1}),
- E_o – activation energy (K),
- T_{ref} – reference temperature = 283.15 (K),
- T_0 – temperature threshold of biological processes start = 227.13 (K),
- T_{soil} – soil temperature at the depth of best fit with the dataset (K).

RESULTS AND DISCUSSION

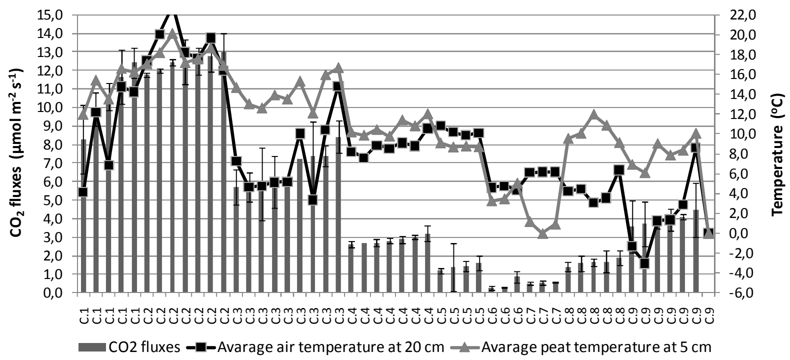
Temperature changes over the measurement campaigns

The air and soil temperature were modeled for the whole experiment and each site based on the temperatures measured permanently on the Eddy Covariance tower and temperatures measured on sites at the time of each measurement. The modeled temperatures showed small, but statistically significant differences between sites (Tab. 1). Site S_1 was the warmest one. It can be concluded generally that the closest the site is located to the middle of the peatland area, the lower air and peat temperatures are. The observed differences between the air and peat substrate temperatures can be related to the type of vegetation (aboveground biomass/plants density) and ground water depth/peat saturation with water. S_1 presents the highest quantity of aboveground biomass in comparison to the other three sites. In the middle of the peatland area, more water is available close to the surface and more energy is used for the evapotranspiration and hence less sensible heat flux (less energy for air heating).

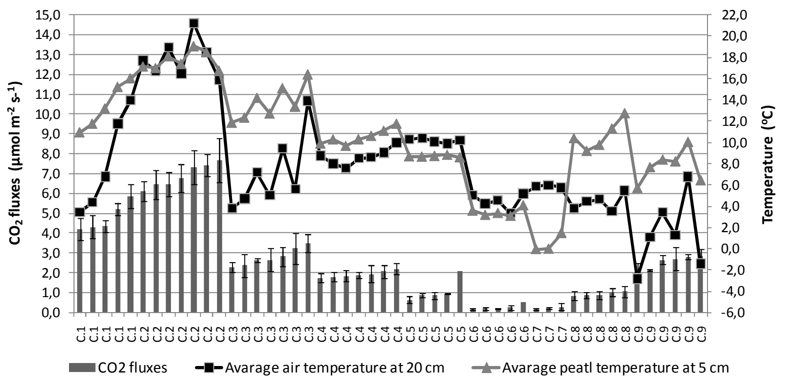
The maximum values of night soil temperatures at 5-cm depth were measured on 07.08.2008 and reached 20.4^{o}C, while the maximum air temperature recorded at the same night was 23.6^{o}C. The minimum value of night soil temperature at the same depth was recorded on 04.03.2009 and fall down to –0.1^{o}C. Whereas, the minimum air temperature was measured in May campaign and reached –3.5^{o}C (Tab. 1, Fig. 1). The night time measurements of CO_2 effluxes during the winter and spring periods were carried out at "warm" nights, when strong frost was not expected (due to the thermal characteristics of the equipment and comfort of researchers). However, this led to the situation, that during the whole winter and early spring campaigns the night-time air temperature did not drop below 0^{o}C (or slightly below), although the peat surface was still frozen (Fig. 1). On the other hand, it was supposed that during the cold nights with temperatures below 0^{o}C, the CO_2 efflux is very close to "0", thus, there were no reasons to carry out measurements in such conditions. Both maximum and minimum values of temperatures were measured at the same site S_1 (Tab. 1).

Table 1. Maximum, minimum and average values of the measured temperatures and CO_2 effluxes

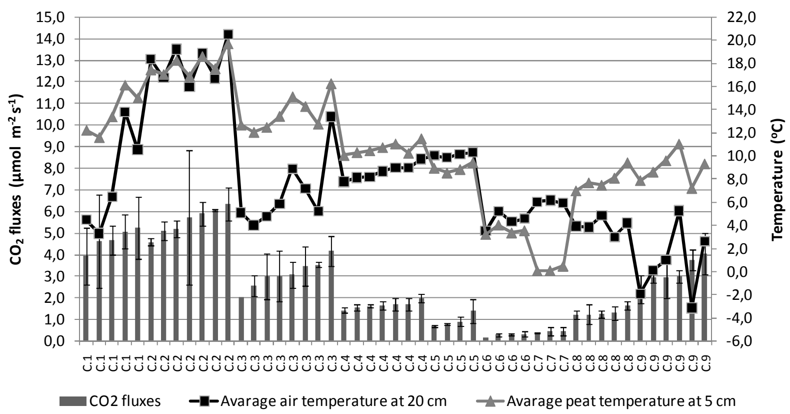
		Flux CO_2	T air 20 cm	T soil –2 cm	T soil –5 cm	T soil –10 cm
		μmol m^{-2} s^{-1}	°C			
S_1	max	13.95	23.6	20.7	20.4	19.2
	min	0.18	–3.5	0.1	–0.1	0.0
	avg	5.28	8.5	10.0	11.0	11.9
S_2	max	8.63	22.5	17.5	19.4	18.7
	min	0.09	–2.9	0.1	–0.1	0.0
	avg	2.72	8.2	9.6	10.7	11.6
S_3	max	7.97	21.4	20.5	19.8	20.0
	min	0.18	–3.4	0.2	0.1	–0.6
	avg	2.72	8.1	9.9	10.7	11.9
S_4	max	12.40	21.4	19.7	19.5	19.7
	min	0.07	–3.1	0.2	0.1	–0.6
	avg	3.69	7.6	9.6	10.5	11.7



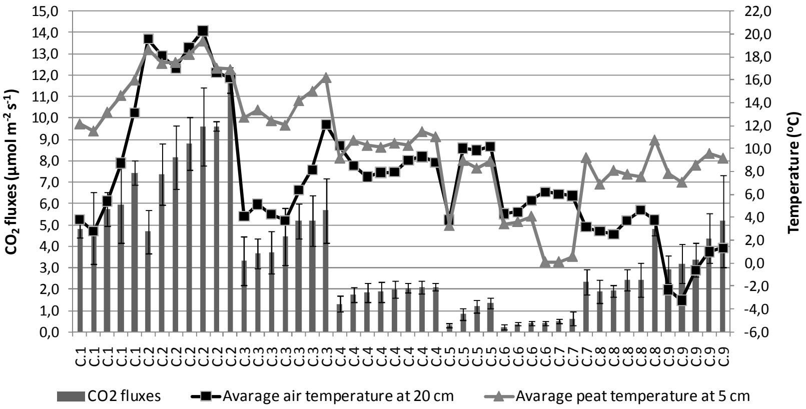
site S_1



site S_2



site S_3



site S_4

Fig. 1. Measured average CO_2 night-time effluxes, air and peat temperatures at the sites S_1-S_4 for different campaigns; (C1: 17-18.07.08; C2: 7-8.08.08; C3: 8-9.09.08; C4: 1-2.10.08; C5: 4-5.11.08; C6: 21-22.12.08; C7: 3-4.03.09; C8: 6-7.04.09; C9:4-5.05.09)

Night-time measured CO_2 effluxes

Night-time CO_2 effluxes measured with the chambers showed essential spatial and temporal differences between the sites (Tab. 1). Similar situation was reported for example by Hirota *et al.* (2006) who measured CO_2 effluxes during the whole year in wetland ecosystem in the Tibetan Plateau and also by Laine *et al.* (2007) in a lowland blanket bog in Ireland.

The highest effluxes were measured in site S_1 (up to 14 µmol m^{-2} s^{-1} at 08.08.2008), where the average CO_2 flux for the whole measuring period reached 5.3 µmol m^{-2} s^{-1} (Tab. 1). Surprisingly, both sites S_2 and S_3 behaved similarly (although the distance between them is about 200 meters) and had the same average values of CO_2 efflux (2.7 µmol m^{-2} s^{-1}). Whereas, the site S_4 behaved similarly to site S_1, although the distance between them is more than 350 meters and the sites are covered with a completely different type of vegetation and the ground water level at S_4 is much closer to the surface (during the most part of the measuring period) than at S_1 (Fig. 2). However, the average CO_2 efflux measured at S_4 is slightly smaller than at site S_1.

The lowest CO_2 effluxes were measured during the winter period (from December 2008 till March 2009), when the peat surface was frozen. Nevertheless, during the winter campaigns some activity of the surface was observed (even through the snow cover), as the measured fluxes were higher than 0. It has to be pointed out that these campaigns were organized during “warm” nights, when air temperature was close to 0^{o}C. As it was proved by Mikan *et al.* (2002), a relatively small increase of the temperature of frozen soils may lead to the increase of CO_2 emission over the winter period. This effect occurs also during our measuring campaigns.

The highest values of night-time CO_2 effluxes were measured in July and August 2008. The night-time CO_2 effluxes measured during the autumn (October – November 2008) were lower than those measured during the spring campaigns of 2009, although the average air temperature of the autumn campaigns was higher than in spring, and soil temperature at 5 cm had similar ranges in both periods (Fig. 1). There were also not essential differences in ground water depth between those periods (Fig. 2). This could lead to the conclusion that the ecosystem respiration of the spring period could be related more to the autotrophic respiration of plants (which starts to develop during that period), than to the peat respiration itself.

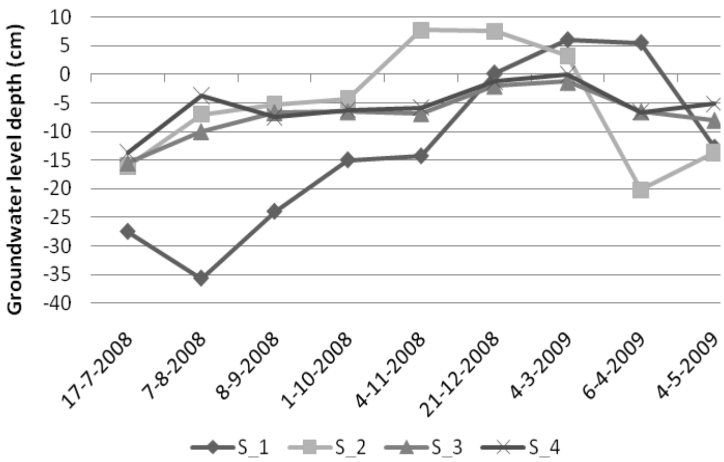
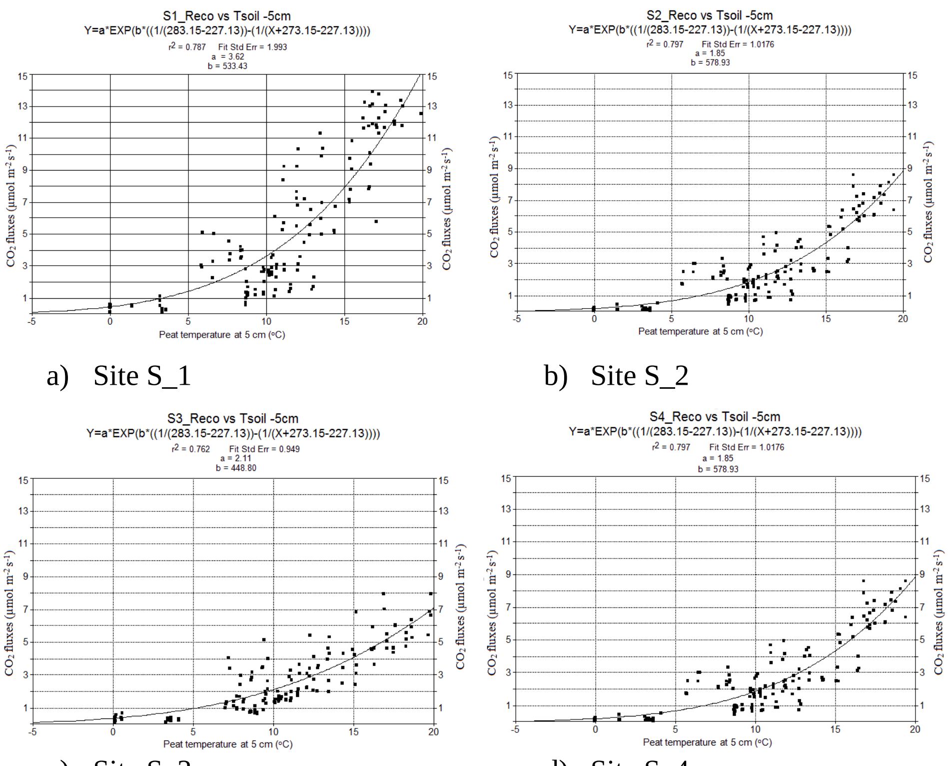


Fig. 2. Average ground water depth within the period of July 2008-May 2009

One of the main drivers controlling the respiration processes (both autotrophic and heterotrophic ones) is temperature (Lloyed and Taylor 1994). The classical Lloyed and Taylor (1994) approach assumes that there is only one pool of carbon – an organic matter of the soil. This does not take into consideration the C pool related to the vegetation that is growing on the surface. Under this assumption Lloyed and Taylor (1994) proved that the soil respiration processes are driven by the soil temperature and in most cases the soil temperature at 5 cm explains the measured respiration rates. However, in our case we are focusing not only on measurements of soil respiration, but the total ecosystem respiration, which consists of the respiration of soil, plants and micro/macrofauna (both autotrophic and heterotrophic types). Due to this the analyzes carried out basing on our data showed that the respiration processes at different campaigns were driven either by soil temperatures (at 2 or 5 cm) or by the air temperature. But, if we consider the whole set of data for the whole measurement period, then the soil temperature at the depth of 5 cm best corresponds to the measured fluxes (the r^2 is the highest and close to 0.8). These analyses were done on the basis of the Lloyed and Taylor (1994) exponential function and their results are presented in Figure 3. Standard parameters of goodness-of-fit statistics as Mean Absolute Error (MAE) was used to assess the Lloyed and Taylor model of relationship between R_{eco} and temperature. The MAE for sites S_1 and S_4 are the highest and are equal to 1.57 and 0.98, respectively. For the sites S_2 and S_3 the MAE is much lower and is close to 0.77 for both sites. Although quite high the MAE values, especially for S1 site, seems to be reasonable to use the Lloyed and Taylor (1994) model for all sites to estimate the R_{eco} fluxes based on the temperature for the whole measurement period. Other authors, for example Hirota *et al.* (2006) and Bubier *et al.* (1998) received similar results and confirmed that soil temperature at 5 cm rules the respiration processes.



a) Site S_1

b) Site S_2

c) Site S_3

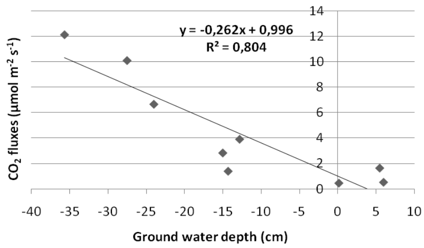
d) Site S_4

Fig. 3. Relationships between the measured CO_2 effluxes and soil temperature at 5 cm for the period 01.06.2008-31.05.2009

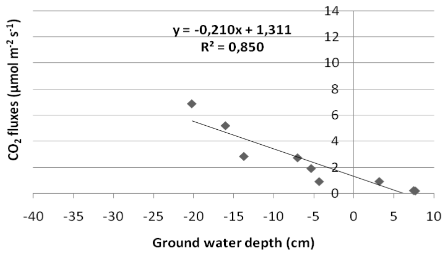
Figure 1 presents differences in the average night-time CO_2 effluxes between the sites. It is conspicuous that with similar soil/peat temperatures, the measured fluxes at the same campaigns are different for each site. This could lead to the general conclusion, that besides temperature, there should be other drivers controlling the ecosystem respiration processes at our sites (e.g. the aboveground plant biomass, the type of vegetation, the peat saturation with water/ground water level depth). For example, the highest fluxes were measured at site S_1 which is dominated by the *Caricetum elatae* communities (Figs. 1 and 3). The biomass of plants in that site is definitely much bigger than in the other sites. On the other hand, the CO_2 effluxes were the lowest at site S_3 dominated by *Menyantho-Sphagnetum teretis,* which correspond also to the lowest biomass. Riutta *et al.* (2007) showed that even in a wetland with a relatively uniform surface topography and uniform vegetation composition, carbon gas dynamics differed markedly between plant communities. Of course, the composition of the plant communities over the sites of Rzecin wetland can be dependent on the nutrients availability, ground water table and, most probably, also the peat structure (dependent on the age and decomposition rate of peat). Nevertheless, it seems that at the sites with heavier aboveground plant biomass (e.g. S_1) an autotrophic respiration can be bigger over night than heterotrophic one and it can constitute the most essential part of the measured ecosystem respiration.

The other driver controlling the respiration processes over Rzecin wetland is related to the peat saturation with water (aeration of the peat) or just the depth of ground water level. Analyses carried out by us proved that there is a clear correlation between ground water depth and average nighttime CO_2 fluxes. It seems that the deeper groundwater table, the higher average nighttime CO_2 effluxes (Fig. 4). The analyses were carried out on the basis of average fluxes calculated for each nighttime campaign and these correlations were not so clear when the individual measurements were used for the analyses. Nevertheless, the received correlations indicate that the ground water table can explain some variability of average nighttime CO_2 fluxes over wetland sites. We have also found that, with the same ground water depth, different average fluxes can be obtained for each site. This is most probably caused by the differences in peat/air temperatures which rule the respiration processes. However, a lot of studies showed that at boreal peatlands the trophic status, above ground net primary productivity, and soil temperatures may be more important to determine ecosystem respiration than water table (e.g. Bubier *et al.* 1998, Silvola *et al*. 1996, Lafleur *et al.* 2005). The water table can play a minor role in predicting daily R_{eco}, but it can be of great importance for predicting seasonal average R_{eco} (Bubier *et al.* 1998).

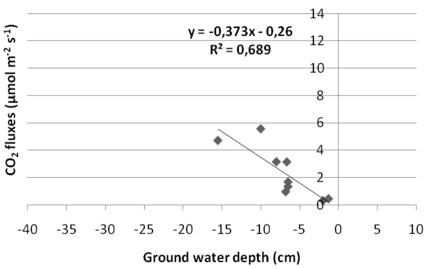
Considering the above, it can be concluded that the ground water table should be taken into account when predicting the average nighttime R_{eco} fluxes and most probably also in modeling of R_{eco} over wetlands.



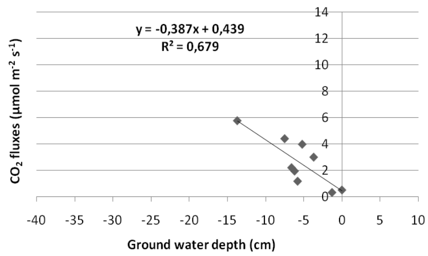
a) Site S_1



b) Site S_2



c) Site S_3



d) Site S_4

Fig. 4. Relationship between the measured average nighttime CO_2 effluxes and the ground water table

Beside the abovementioned drivers controlling the Ecosystem Respiration there could be others (related to plant activity) that have not been considered here. However, classical approach of R_{eco} modeling, which is based on the thermodynamic principles and simple first-order exponential equation with temperature as the only determinant, has recently come in for criticism (Craine *et al.* 1999). The reason is that the temperature-dependent models poorly reflect the complex nature of different components of ecosystem respiration as well as drivers controlling the autotrophic and heterotrophic respiration types (*Craine et al.* 1999, Davidson *et al.* 2006, Larsen *et al.* 2007).

Modeling of night-time Ecosystem Respiration (R_{eco})

The results of modeling are presented in Figures 6 and 7. As it has been discussed before, the modeled estimates of R_{eco} fluxes in site S_1 were much higher during the summer time of 2008, than in the other sites. The maximum night-time flux modeled for site S_1 exceeded 5 g CO_2-C m^{-2} $night^{-1}$ in August 2008, whereas for S_4 (most similar) has not exceeded 4 g CO_2-C m^{-2} $night^{-1}$ (Fig. 6). For the rest of the modeling period the fluxes were much lower and differences between the sites were smaller than for the summer time.

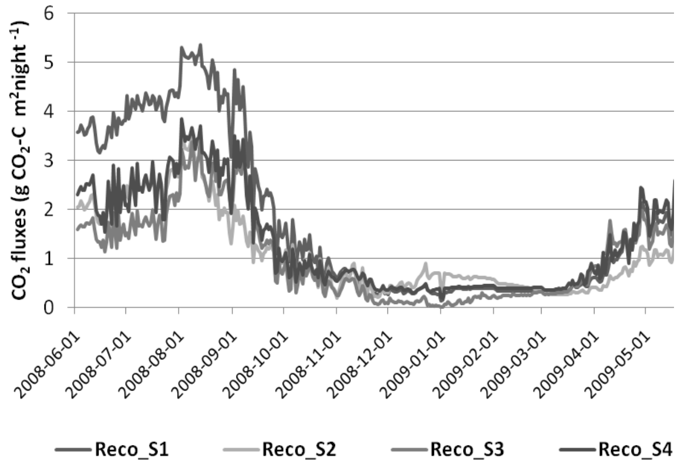


Fig. 6. Courses of the modeled nighttime ecosystem respiration (R_{eco}) for all investigated sites over the study period 01.06.2008-31.05.2009

The cumulative modeled nighttime ecosystem respiration for the whole measuring period showed essential differences between the sites (Fig. 7). The fluxes cumulated only for the night-time periods reached 650 g CO_2-C m^{-2} yr^{-1} at site S_1, 500 g CO_2-C m^{-2} yr^{-1} for S_4 and have not exceeded 400 g CO_2-C m^{-2} yr^{-1} for both S_2 and S_3 sites. The obtained values seem to be very high in comparison to the results of other authors. However, it has to be noticed that most of the results are related to the R_{eco} modeled on the basis of day-time measurements and calculated for the whole day. As a result of this the direct comparison of the obtained results is rather impossible. However, the majority of the published data related to the R_{eco} measurements on wetlands gave much lower values. For example, Drösler (2005) estimated an annual daily R_{eco} at about 443 g CO_2-C m^{-2} yr^{-1} in a degraded bog in the southern Bavaria (Germany). Wickland *et al.* (2001) obtained the value of 360 g CO_2-C m^{-2} yr^{-1} in an alpine wetland in the Rocky Mountains (USA) and Heikkenen *et al.* (2004) reported the value of 232 g CO_2-C m^{-2} yr^{-1} in an ombrotrophic bog in the eastern Russia. There are only two papers which presented directly the results of the chamber nighttime measurements of R_{eco} in peatland sites. The Alm *et al.* (1993) published nighttime R_{eco} values measured only for one night, while Schnider *et al.* 2009 published the results of three months chamber campaign. These results, although very useful, cannot be applied for the validation of our modeled results.

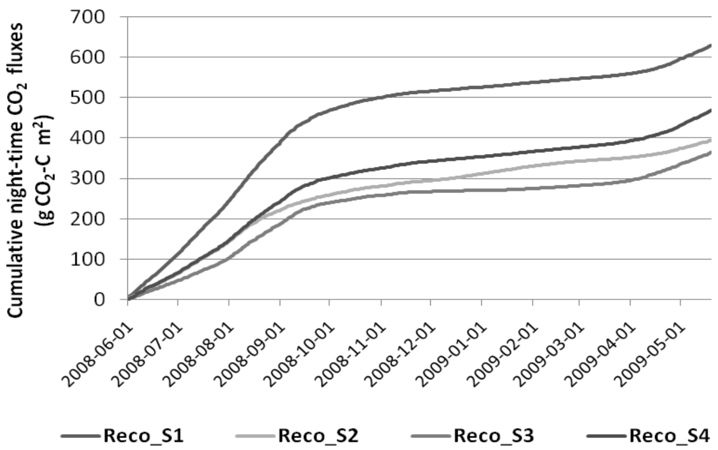


Fig. 7. Cumulative course of night-time ecosystem respiration (R_{eco}) for all investigated sites over the study period 01.06.2008-31.05.2009

Nevertheless, considering big differences between the cumulated nighttime R_{eco} values and those received during the daily measurements (the abovementioned papers), it can be concluded that nighttime chamber measurements of ecosystem respiration can be essentially overestimated. It was shown, for example by Lavigne *et al.* (1997), that the modeled estimates of R_{eco} using chamber measurements can be even 20-42% higher than the nocturnal eddy covariance measurements. The largest differences between the nocturnal measurements of CO_2 fluxes conducted by means of chamber techniques and eddy covariance were reported by Oechel *et al.* (1998) for late night and early morning. On the other hand, the nighttime eddy covariance measurements of CO_2 fluxes carried out during the stable conditions with low turbulence are essentially underestimated (e.g. Zamolodchikov 2003). It was proved by La Dantec *et al.* (1999) and Schnider *et al.* (2009), that the chamber measurements of CO_2 fluxes carried out during calm night conditions can cause the disturbance of stratified air conditions and finally lead to the overestimation of CO_2 fluxes when they are compared to the undisturbed situation. Therefore, Schnider *et al.* (2009) recommended to apply CO_2 gradient measurements above and under the peat surface to estimate CO_2 effluxes during calm stable night conditions. Under stable nighttime conditions chamber measurements can be seriously biased, and therefore, the suitability of chamber technique for the nighttime measurements of CO_2 effluxes (in order to replace the nighttime eddy covariance measurements) might be limited (Schnider *et al.* 2009).

CONCLUSIONS

1. The measured as well as the modeled nighttime CO_2 effluxes differ among the sites. The differences between effluxes were most significant during summer (the highest activity of plants and microbes due to the highest temperatures). The cumulative nighttime modeled R_{eco} was the highest at the site with the highest amount of biomass and lowest ground water depth. Thus, it has been confirmed that the ecosystem respiration in wetland ecosystem is controlled not only by the peat/air temperature, but also by the plant biomass and/or the saturation of peat substrate with water/ground water depth. The nature of the respiration processes is so complex, that it is difficult to define precisely whether autotrophic and/or heterotrophic processes dominated the measured fluxes at each site and during each measuring campaign.
2. Taking the above into consideration, it can be concluded that the CO_2 effluxes modeled on the basis of the single first-order exponential equation, with temperature as the only determinant, cannot be suitable for the estimation of the ecosystem respiration. Due to the complex nature of both autotrophic and heterotrophic types of respiration it seems reasonable to include in modeling other drivers that may control the respiration processes (plant biomass, ground water depth etc.).
3. The chamber measurements of nighttime CO_2 effluxes can be seriously biased, and can lead to the overestimation of measured fluxes. Due to this the applicability of nighttime chamber measurements for R_{eco} estimation during the stable conditions can be questionable.

Acknowledgements

The presented studies has been supported by the following European Community's Sixth Framework Programme projects: a GREENFLUX-TOK contract no. MTKD-CT-2006-042445 and CARBOEUROPE-IP contract no. GOCE-CT-2004-505572

REFERENCES

Acosta M., Janouš D., Marek M.V., 2004. Soil surface CO_2 fluxes in a Norway spruce stand. Journal of Forest Science, 50(12), 573-578.

Alm, J., A. Talanov, S. Saarnio, J. Silvola, E. Ikkonen, H. Aaltonen, H. Nykanen, Martikainen P.J., 1997. Reconstruction of the carbon balance for microsites in a boreal oligotrophic pine fen, Finland. Oecologia, 110, 423-431.

Alm J., Schulman L., Walden J., Nykanen H., Martikainen P.J., Silvola J., 1999. Carbon balance of a boreal bog during a year with an exceptionally dry summer. Ecology, 80, 161-74.

Aubinet M., Grelle A., Ibrom A., Rannik U., Moncrieff J., Foken T., Kowalski A.S., Martin P.H., Berbigier P., Bernhofer C., Clement R., Elbers J., Granier A., Grunwald T., Morgenstern K., Pilegaard K., Rebmann C., Snijders W., Valentini R., Vesala T., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Adv. Ecol. Res., 30, 113-175.

Aurela M., Laurila T., Tuovinen J.P., 2001. Seasonal CO_2 balances of a subarctic mire. J. Geophys. Res., 106, 1623-1637.

Baldocchi D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems. Past, present and future. Global Change Biology, 9(4), 479-492.

Barford C.C., Wofsy S.C., Goulden M.L., et al. 2001. Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. Science, 294, 1688-1691.

Bekku Y,. Koizumi H,. Oikawa T,. Iwaki H., 1997. Examination of four methods for measuring soil respiration. Applied Soil Ecology, 5, 247-254.

Brown D.A., 1998. Gas production from an ombrotrophic bog – effect of climate change on microbial ecology. Climate Change, 40, 277-284.

Bubier J.L., Crill P.M., Moore T.R., Savage K., Varner R.K., 1998. Seasonal patterns and controls on net ecosystem CO_2 exchange in a boreal peatland complex. Global Biogeochem. Cycles, 12, 703-714.

Chojnicki B.H., Urbaniak M., Józefczyk D., Augustin J., Olejnik J., 2007. Measurements of gas and heat fluxes at Rzecin wetland. in: Wetlands: Monitoring, Modeling and Management. (eds) Okruszko *et al*., Taylor & Francis Group. London, 125-132.

Chojnicki B.H, Michalak M., Acosta M., Juszczak R., Augustin J., Drösler M., Olejnik J., 2010. Measurements of carbon dioxide fluxes by chamber method at Rzecin wetland ecosystem in Poland. Polish Journal of Environmental Studies (in printing).

Clymo R.S., Turunen J., Tolonen K., 1998. Carbon accumulation in peatland. Oikos, 81, 368–388.

Craine J.M., Wedin D.A., Chapin F.S., 1999. Predominance of ecophysiological controls on soil CO_2 flux in a Minnesota grassland. Plant Soil, 207, 77-86.

Davidson E.A., Janssens I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440, 165-173.

Drösler M., 2005. Trace gas exchange and climatic relevance of bog ecosystem, Southern Germany. PhD Dissertation, Lehrstuhl für Vegetationsokologie, Department für Ökologie, Technischen Universität München.

Gajewski K., Viau A., Sawada M., Atkinson D., Wilson S., 2001. Sphagnum peatland distribution in North America and Eurasia during the past 21,000 years. Global Biogeochemical Cycles 15, 297-310.

Gorham E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol Appl, 1, 185-192.

Goulden M.L., Munger J.W., Fan S.M., Daube B.C., Wofsy S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance. Methods and critical evaluation of accuracy. Global Change Biology, 2, 169-182.

Heikkinen J.E.P., Virtanen T., Huttunen J.T., Elsakov V., Martikainen P.J., 2004. Carbon balance in East European tundra. Global Biogeochemical Cycles, 18, GB1023.

Hirota M., Tang Y., Hu Q., Hirata S., Kato T., Mo W., Cao G., Mariko S., 2006. Carbon Dioxide Dynamics and Controls in a Deep-water Wetland on the Qinghai-Tibetan Plateau. Ecosystems, 9, 673-688.

Hutchinson G.L., Livingston G.P., Healy W., Striegl R.G., 2000. Chamber measurement of surface-atmosphere trace gas exchange. Numerical evaluation of dependence on soil, interfacial layer, and source/sink properties. Journal of Geophysical Research, 105(D7), 8865-8875.

IPCC, 2007. Climate Change 2007. The Physical Science Basis – Summary for Policymakers. http://www.ipcc.ch/SPM2feb07.pdf.

Laine A., Byrne K., Kiely G., Tuittila E.S., 2007. Patterns in Vegetation and CO_2 Dynamics along a Water Level Gradient in a Lowland Blanket Bog, Ecosystems, 10, 890-905.

Le Dantec V., Epron D., Dufrene E., 1999. Soil CO_2 efflux in a beech forest: Comparison of two dynamic systems. Plant Soil, 214, 125-132.

Lafleur P.M., 1999. Growing season energy and CO_2 exchange at a subarctic boreal wood land. Journal of Geophysical Research, 104(D8), 9571-9580.

Lafleur P.M., Roulet N.T., Bubier J.L., Frolking S., Moore T.R., 2003. Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog. Global Biogeochem. Cycles, 17(2), 1036.

Lafleur P.M., Moore T.R., Roulet N.T., Frolking S., 2005. Ecosystem respiration in a cool temperate bog depends on peat temperature but not water table. Ecosystems, 8, 619-629.

Larsen K.S., Ibrom A., Beier C., Jonasson S., Michelsen A., 2007. Ecosystem respiration depends strongly on photosynthesis in a temperate health. Biogeochemistry, 85, 201-213.

Lavigne M.B., Ryan M.G., Anderson E.E., Baldocchi D.D., Crill P.M., Fitzjarrald D.R., Goulden M.L., Gover S.T., Massheder J.M., McCaughey J.H., Rayment M., Striegl R.G., 1997. Comparing nocturnal eddy covariance measurements to estimates of ecosystem respiration made by scaling chamber measurements at six coniferous boreal sites. J. Geophys. Res., 102(D24), 28977-28985.

Livingston, G.P., Hutchinson, G.L., 1995. Enclosure-based measurement of trace gas exchange: applications and sources of error. In: Matson, P.A., Harriss, R.C. (Eds.), Biogenic Trace Gases: Measuring Emissions from Soil and Water. Blackwell Science, Cambridge, 14-50.

Livingston G.P., Hutchinson G.L., Spartalian K., 2006. Trace gas emission in chambers: A non-steady-state diffusion model. Soil Science Society of American Journal, 70, 1459-1469.

Lloyd J., Taylor J.A., 1994. On the temperature dependence of soil respiration. Functional Ecology, 8, 315-323.

Mikan C.J., Schimel J.P., Doyle A.P., 2002. Temperature controls of microbial respiration in arctic tundra soils above and below freezing. Soil Biology & Biochemistry, 1785-1795.

Münchmeyer U., 2001. Zur N-Umsetzung in degradierten Niedermoorböden Nordostdeutschlands unter besonderer Berücksichtigung der N-Mineralisierung und des Austrages gasförmiger N-Verbindungen. Dissertation Universität Greifswald. Diss. University of Hohenheim, Germany. Verlag Grauer, Beuren/Stuttgart. (dt.) ISBN 3-86186-394-4

Oechel W.C., Vourlitis G.L., Brooks S., Crawford T.L., Dumas E., 1998. Intercomparison among chamber, tower, and aircraft net CO_2 and energy fluxes measured during the Arctic System Science Land-Atmosphere-Ice Interactions (ARCSS-LAII) Flux Study, J. Geophys. Res., 103(D22), 28,993-29,003.

Pumpanen J., Kolari P., Ilvesniemi H., Minkkinen K., Vesala T., Niinisto S., Lohila A., Larmola T., Morero M., Pihlatie M., Janssens I., Yuste J.C., Grunzweig J.M., Reth S., Subke J.A., Savage K., Kutsch W., Ostreng G., Ziegler W., Anthoni P., Lindroth A., Hari P., 2004. Comparison of different chamber techniques for measuring soil CO_2 efflux. Agricultural and Forest Meteorology, 123, 159-176.

Reth S., Gockede M., Falge E., 2005. CO_2 efflux from agricultural soils in Eastern Germany – comparison of a closed chamber system with eddy covariance measurements. Theor. Appl. Climatol. 80, 105-120.

Riutta T., Laine J,. Aurela M., Rinne J., Vesala T., Laurila T., Haapanala S., Pihlatie S., Tuittila ES., 2007. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem, Tellus, 59B, 838-852.

Schnider J., Kutzbach L., Schulz S., Wilmking M., 2009. Overestimation of CO_2 respiration fluxes by closed chamber method in low turbulence nighttime conditions. Journal of Geophysical Research, 114, G03005.

Silvola J., Alm J., Ahlholm U., Nykanen H., Martikainen P.J., 1996. CO_2 fluxes from peat in boreal mires under varying temperature and moisture conditions. Journal of Ecology, 84, 219-228.

Van Gorsel E., Leuning R., Cleugh H.A., Keith H., Suni T., 2007. Nocturnal carbon efflux. Reconciliation of eddy covariance and chamber measurements using an alternative to the u*-threshold filtering technique. Tellus, 59(3), 397-403.

Wickland K.P., Striegl R.G., Mast M.A., Clow D.W., 2001. Carbon gas exchange at a southern Rocky Mountain wetland, 1996-1998. Global Biogeochem Cycles, 15, 321-350.

Wojterska M., 2001. The Vegetation of Wielkopolska and Southern Pomerania lakeland regions: Field session guide 52 (in Polish). Polish Botanical Society Meeting, 24-28 September 2001.

Zamolodchikov D.G., Karelin D.V., Ivaschenko A.I., Oechel W.C., Hastings S.J., 2003. CO_2 flux measurements in Russian Far East tundra using eddy covariance and closed chamber techniques. Tellus, Ser. B., 55, 879-892.

10. SUMMARY

The changes in chemical and physical features of the atmosphere very often influence, both directly and indirectly, human life conditions. The description and parameterization of the exchange processes between the Earth surface and the atmosphere require the development of both new scientific ideas and measuring techniques. This monograph contains the description of the state-of-the-art atmospheric studies where novel measuring techniques were applied for both gas fluxes and gas concentration studies. These studies were conducted in different landscape elements under Polish climate conditions.

The profile methods presented in the first chapter of this monograph include theoretical and practical considerations about the application Bowen ratio profile method. These techniques have been commonly used since 1980s for heat and water balance investigations of the ecosystem active surface. Their application has been recently extended to other gas fluxes estimations e.g. ammonia, methane etc.

The eddy covariance (EC) technique has become the main method of heat and mass exchange estimation over the ecosystems. Both theoretical and technical background of the EC method as well as preliminary estimations of carbon dioxide and water vapor fluxes are described in the second chapter. So is the parameterization of exchange processes between the forest and the atmosphere. The forest EC system in Tuczno that was the source of data for those studies is the first permanent measuring station in Poland operating since the end of 2008.

The chamber technique can be considered as an alternative or supplement for the EC method, under certain conditions e.g. small scale of measurements, lack of turbulence in the atmosphere. The manual chamber measurements are not often conducted in terrain conditions, e.g. monthly since this method requires considerable labor input. This technique must be applied along with such measurements as e.g. air temperature and solar radiation that allow to estimate the fluxes between each chamber measurement sessions. Both the chamber technique and calculation procedures are presented in the third chapter. These studies were conducted at Rzecin wetland where the Meteorology Department measuring station has been operating since 2003.

Urban areas in Poland are considerable emitter of carbon dioxide to the atmosphere since most of the Polish homesteads are coal heat dependent. The results of EC measurements that were carried out in Łódź city center during the period from July 2006 to July 2009 are presented in the fourth chapter. The studied area is permanent and season independent emitter of CO_2. The summer fluxes observed over Łódź are the smallest during the whole year because of the com-

bination of plants' photosynthetic activity and very reduced carbon dioxide city emission.

The nitrogen oxide affects directly human health and it is noticeable in the city centers.

The goal of the study described in the fifth chapter of this monograph was the presentation of the changes in the concentration of tropospheric ozone in comparison with fluctuations of nitrogen oxide concentration. The observations show the impact of meteorological conditions on photochemical processes appearing in the atmosphere over Warsaw.

Natural radioactivity in the atmospheric boundary layer is mainly determined by radon (222Rn) and radon progeny. This is the most important radioactive gas observed in the atmosphere in Poland. Chapter six contains the study of the temporal variability of near-surface 222Rn concentration in relation to urban and rural meteorological parameters (i.e. air temperature, thermal vertical gradient, wind speed) and urban heat island phenomenon.

The carbon dioxide exchange between the ecosystems and the atmosphere depends on the state of development of its vegetation canopy. The Leaf Area Index (LAI) is a commonly used parameter that expresses the ratio of alive leaf to the ground area. The estimation of the value of this ratio in forest conditions can be conducted by application of different methods. The hemispherical photography technique was presented in chapter seven as common and non destructive method of LAI estimation in the forest. The measurements were carried out at Tuczno site, the first permanent forest EC tower established by the Meteorology Department scientific team.

Methane is one of the most important gases in terms of global warming potential. The wetlands are described in literature as one of strongest sources of this gas in the environment. The measurement of this gas is difficult since its concentration in the atmospheric air is very low. The Relaxed Eddy Accumulation (REA) approach has been recently considered as a very reliable method for low concentrated gases fluxes measurements. The first polish REA was developed and successfully tested by scientific workers of the Meteorology Department, Poznan University of Life Sciences. The description of these activities is included in chapter eight.

The possibility of chamber technique application under nighttime (lack of turbulence) conditions is the advantage of this method in comparison to the EC technique. The description of night time chamber measurements and studies of the obtained data are presented in the last chapter of this monograph.

11. STRESZCZENIE

Zmiany składu chemicznego atmosfery wpływają na warunki życia człowieka zarówno w sposób bezpośredni, jak i pośredni. Zmiany te zależą między innymi od procesów wymiany między powierzchnią Ziemi a atmosferą, których opis i parametryzacja wymagają rozwoju zarówno teorii jak i technik pomiarowych ich dotyczących. W niniejszej monografii przestawione zostały nowoczesne techniki pomiarowe, które są obecnie stosowane do oceny wielkości strumieni oraz stężeń określonych gazów w atmosferze.

Wszystkie przedstawione wyniki badań zostały uzyskane w polskich warunkach klimatycznych nad różnymi typami użytkowania terenu.

W pierwszym rozdziale zostały przedstawione zarówno teoretyczne, jak i praktyczne rozważania dotyczące wykorzystania metody Bowena. Technika ta jest stosowana z powodzeniem od lat 80-tych do badań nad wymianą pary wodnej i ciepła miedzy powierzchnią czynną a atmosferą. Zastosowanie tej metody w ostatnich latach zostało rozszerzone do tez do badań pomiarów strumieni innych gazów, takich jak amoniak czy metan.

Technika kowariancji wirów jest obecnie uznawana za standardową podczas pomiarów strumieni masy i energii nad ekosystemami. Teoretyczne i techniczne podstawy tej metody, a także wstępne wyniki pomiarów zostały przedstawione w drugim rozdziale monografii. Opisano również parametryzacje tych procesów. Źródłem danych był system kowariancyjny zainstalowany w końcu 2008 nad lasem sosnowym w Tucznie.

Metody komorowe mogą być traktowane zastępczo lub jako uzupełnienie pomiarów wykonanych przy pomocy system kowariancyjnego np. w małej skali przestrzennej lub w warunkach braku turbulencji w atmosferze. Pomiary komorami obsługiwanymi ręcznie w warunkach terenowych są wykonywane z małą częstotliwością (zwykle raz na miesiąc) z powodu wymaganego dużego wkładu pracy fizycznej. Technika ta musi być stosowana równolegle wraz z pomiarami takich charakterystyk jak temperatura powietrza i promieniowanie całkowite, co pozwala na interpolację uzyskanych wyników między poszczególnymi sesjami pomiarowymi. Zarówno technika pomiarowa, jak i obliczeniowa stosowane w metodzie komorowej zostały zaprezentowane w trzecim rozdziale. Badania te przeprowadzone zostały na terenie stacji pomiarowej w Rzecinie, której obsługą zajmują sie pracownicy Katedry Meteorologii Uniwersytetu Przyrodniczego w Poznaniu od końca 2003 roku.

Tereny zurbanizowane w Polsce są silnym emiterem dwutlenku węgla, ponieważ ciepło potrzebne w gospodarstwach domowych, pochodzi ze spalania węgla kamiennego. Pomiary strumieni dwutlenku węgla przy pomocy system kowariancyjnego, które wykonywano w latach od 2006 do 2009 nad Łodzią zostały zaprezentowane w czwartym rozdziale pracy. Obszar ten jest stałym (niezależnie od pory roku) emiterem dwutlenku węgla. Letnia emisja CO_2 obserwowana nad Łodzią jest najmniejsza z całego roku głównie z powodu silnej aktywności fotosyntetycznej roślin i mniejszej aktywności grzewczej.

Tlenki azotu wpływają bezpośrednio na stan zdrowia ludzkiego i fakt ten jest szczególnie zauważalny w centrach dużych miast. Celem badań przedstawionych w piątym rozdziale monografii była prezentacja zmian steżeń tlenków azotu oraz ozonu w przygruntowej warstwie powietrza. Obserwacje wskazują na wpływ procesów fotochemicznych na tworzenie się badanych związków w atmosferze nad Warszawą.

Naturalna radiacyjność atmosfery wynika głównie z występowania w niej radonu (222Rn). Jest on także obserwowany w Polsce. Rozdział szósty zawiera wyniki badań czasowej zmienności stężenia tego pierwiastka przy powierzchni ziemi. Wyniki pomiarów stężenia radonu zostały przedstawione na tle parametrów metrologicznych w warunkach miejskich oraz poza miastem.

Wielkości i kierunek wymiany dwutlenku węgla między atmosferą a podłożem zależy w dużej mierze od stanu rozwoju szaty roślinnej. Współczynnik Ulistnienia (ang. LAI) jest powszechnie stosowanym parametrem do opisu szaty roślinnej i jest to stosunek powierzchni żywych liści do powierzchni gruntu, nad którym sie znajdują. Ocena wartości tego parametru w warunkach leśnych odbywa sie przy zastosowaniu wielu różnych metod. Technika fotografii hemisferycznej została zaprezentowana, jako jedna z niedestruktywnych metod oceny LAI w lesie. Badania te były prowadzone na pierwszej leśnej stacji pomiarowej, na której wykonuje sie pomiary metodą kowariancji wirów, w Tucznie.

Metan jest ostatnio postrzegany jako jeden z najważniejszych gazów szklarniowych związanych z obserwowanym obecnie dodatnim wymuszeniem radiacyjnym na Ziemi. Tereny podmokłe są opisywane w literaturze, jako jedno z największych źródeł emisji tego gazu do atmosfery. Pomiary strumieni metanu sprawiają sporą trudność z powodu jego niskiego stężenia w powietrzu. Rozszerzona Metoda Akumulacji Wirów (ang. REA) jest obecnie uznawana za stosunkowo łatwą i pewną metodę pomiarów strumieni gazów występujących w atmosferze w małym stężeniu. Pierwszy w Polsce system REA do pomiarów strumieni metanu został zbudowany i przetestowany w warunkach terenowych przez pracowników Katedry Meteorologii Uniwersytetu Przyrodniczego w Poznaniu. Wyniki tych prac przedstawiono w rozdziale ósmym.

Jedna z największych cech pozytywnym metody komorowej jest możliwość zastosowania jej w warunkach braku turbulencji, wtedy gdy metoda kowariancji wirów nie może być wykorzystywana. Wyniki badań w takich warunkach (najczęściej nocą) zostały przedstawione w ostatnim rozdziale monografii.

W serii *Acta Agrophysica*
ukazały się następujące pozycje:

Nr 0: Marek A. Malicki: *Wpływ fizycznych właściwości gleby na elektryczne parametry układu elektrody-gleba w aspekcie pomiaru jej wilgotności i zasolenia*, Lublin 1993.

Nr 1: Józef Horabik: *Wpływ właściwości mechanicznych ziarna pszenicy na rozkład obciążenia w zbiorniku*, Lublin 1994.

Nr 2: Jerzy Niewczas: *Ocena uszkodzeń mechanicznych ziarna pszenicy wykrywanych techniką rentgenograficzną*, Lublin 1994.

Nr 3: Riccardo Paolo Bennicelli: *Wpływ zlokalizowanego stresu tlenowego w glebie na rozwój korzeni i części nadziemnych kukurydzy* (*modelowe badania rizotronowe*), Lublin 1994.

Nr 4: Marek Molenda, Józef Horabik, Marian Grochowicz, Bogusław Szot: *Tarcie ziarna pszenicy*, Lublin 1995.

Nr 5: Wiktor Pietrzyk: *Electric field influence on grain*, Lublin 1996.

Nr 6: Jerzy Tys: *Czynniki kształtujące właściwości agrofizyczne rzepaku*, Lublin 1997.

Nr 7: Henryk Czachor: *Geometria fazy stałej i przestrzeni porów w rolniczych ośrodkach granularnych na przykładzie gleby mineralnej*, Lublin 1997.

Nr 8: Andrzej L. Marciniak, Andrzej Fijołek, Jerzy Podgórski, Piotr Sieczka: *Wariacyjne metody tworzenia modeli roślinnych*, Lublin 1997.

Nr 9: Ryszard T. Walczak, Cezary Sławiński, Henryk A. Sobczuk, Jan Gliński: *Aspekt hydrologiczny w modelu EURO-ACCESS* (*Agroclimatic Change and European Soil Suitability*), Lublin 1998.

Nr 10: Praca zbiorowa: *Profesor Bohdan Dobrzański - sesja z okazji 10-tej rocznicy śmierci*, Lublin 1998.

Nr 11: Henryk A. Sobczuk: *Opis stanu fizycznego gleby jako ośrodka nieuporządkowanego na przykładzie krzywych retencji wody*, Lublin 1998.

Nr 12: Marek Molenda: *Wpływ struktury złoża nasion na stan naprężenia*, Lublin 1998.

Nr 13: Bohdan Dobrzański jr: *Mechanizmy powstawnia uszkodzeń nasion roślin strączkowych*, Lublin 1998.

Nr 14: Jarosław Pytka, Krystyna Konstankiewicz: *Metody wyznaczania naprężeń i przemieszczeń w glebie pod obciążeniem*, Lublin 1998.

Nr 15: Grzegorz Józefaciuk: *Zmiany własności powierzchniowych gleb i minerałów ilastych w procesach zakwaszania i alkalizacji. Badania modelowe*, Lublin 1998.

Nr 16: Wiktor Pietrzyk, Stanisław Grundas, Marek Horyński, Andrzej Sumorek: *Wykorzystanie pola elektrostatycznego i ozonu do obniżania energochłonności procesu suszenia ziarna zbóż*, Lublin 1998.

Nr 17: Mieczysław Hajnos: *Energia powierzchniowa i wielkości jej składowych jako parametry określające zwilżalność i stan agregacyjny wybranych minerałów ilastych i gleb*, Lublin 1999.

Nr 18: Bogusław Szot: *Właściwości agrofizyczne amarantusa* (*Amaranthus cruentus* L.), Lublin 1999.

Nr 19: Marek A. Malicki: *Metodyczne zagadnienia monitoringu statusu wody w wybranych materiałach biologicznych*, Lublin 1999.

Nr 20: Jan Gliński, Krystyna Konstankiewicz: *Agrofizyka dla środowiska i bezpiecznej produkcji biologicznej*, Lublin 1999.

Nr 21: Piotr Baranowski, Wojciech Mazurek, Ryszard T. Walczak: *Zastosowanie termografii do badania stresu wodnego roślin i ewapotranspiracji rzeczywistej*, Lublin 1999.

Nr 22: Zbiór publikacji: *Procesy agrofizyczne: monitorowanie i modelowanie*, Lublin 1999.

Nr 23: Zbiór publikacji: *Procesy degradacji gleb i metody ich rekultywacji,* Lublin 1999.

Nr 24: Zbiór publikacji: *Fizyczne właściwości rolniczych ośrodków o strukturze dyskretnej*, Lublin 1999.

Nr 25: Stefan Szwaj, Adam Pukos: *Plowing theory*, Lublin 2000.

Nr 26: Zbiór publikacji: *Degradation of peat soils and differentiation of habitat conditions of hydrogenic areas*, Lublin 2000.

Nr 27: Grzegorz Szwed: *Kształtowanie fizycznych i technologicznych cech nasion rzepaku w modelowanych warunkach przechowywania*, Lublin 2000.

Nr 28: Teresa Włodarczyk: *Emisja i absorpcja N_2O na tle emisji CO_2 w glebach brunatnych w zróżnicowanych warunkach oksydoredukcyjnych*, Lublin 2000.

Nr 29: Bogusław Usowicz: *Statystyczno-fizyczne modele przepływu masy i energii w ośrodku porowatym*, Lublin 2000.

Nr 30: Barbara Witkowska-Walczak: *Wpływ struktury agregatowej gleb mineralnych na ich hydrofizyczne charakterystyki.* (*Badania modelowe*), Lublin 2000.

Nr 31: Marek Kotowski , Urszula Kotowska: *Uwalnianie i migracja glinu, cynku, miedzi i ołowiu w glebach bielicoziemnych pod wpływem zakwaszania*, Lublin 2000.

Nr 32: Jan Gliński, Witold Stępniewski, Zofia Stępniewska, Janusz Ostrowski, Teresa Włodarczyk, Małgorzata Brzezińska: *Agroekologiczne aspekty warunków tlenowych gleb ornych*, Lublin 2000.

Nr 33: Janusz Stawiński, Jan Gliński, Janusz Ostrowski, Zofia Stępniewska, Zofia Sokołowska, Grzegorz Bowanko, Grzegorz Józefaciuk, Alicja Księżopolska, Dorota Matyka-Sarzyńska: *Przestrzenna charakterystyka powierzchni właściwej gleb ornych Polski,* Lublin 2000.

Nr 34: Zbiór publikacji: *Klimat pola uprawnego*, Lublin 2000.

Nr 35: Zbiór publikacji: *The role of physical and physicochemical properties of soils in functioning of ecosystems*, Lublin 2000.

Nr 36: Piotr Gliński, Ryszard Dębicki: *Ocena zagrożeń erozyjnych oraz charakterystyka jakości wód przy zastosowaniu symulacji komputerowej*, Lublin 2000.

Nr 37: Zbiór publikacji: *Fizyczne właściwości wybranych materiałów roślinnych*, Lublin 2000.

Nr 38: Zbiór publikacji: *Czynniki agrofizyczne środowiska warunkujące wzrost i rozwój roślin*, Lublin 2000.

Nr 39: Dorota Wójcicka-Migasiuk: *Zastosowanie metody potencjałów węzłowych do analizy i projektowania instalacji słonecznych ciepłej wody*, Lublin 2001.

Nr 40: Marek Horyński: *Wpływ pola elektrostatycznego na właściwości elektryczne zbóż*, Lublin 2001.

Nr 41: Andrzej Sumorek: *Wpływ pola elektrycznego na konwekcyjne suszenie ziarna zbóż*, Lublin 2001.

Nr 42: Wiktor Pietrzyk: *Modele ziarniaków zbóż stosowane w analizie elektrodynamicznej,* Lublin 2001.

Nr 43: Wiktor Pietrzyk, Stanisław Grundas, Marek Horyński, Andrzej Sumorek, Marek Ścibisz, Stanisław Walusiak: *Uzwojenia bifilarne do odpylania w przemyśle rolno-spożywczym,* Lublin 2001.

Nr 44: Jerzy Tys, Roman Rybacki: *Rzepak - jakość nasion, procesy zbioru, suszenia, przechowywania*, Lublin 2001.

Nr 45: Zbiór publikacji: *Właściwości fizyczne niektórych roślin, owoców i warzyw*, Lublin 2001.

Nr 46: Zbiór publikacji: *Właściwości fizyczne nasion niektórych roślin uprawnych i surowców przemysłu spożywczego*, Lublin 2001.

Nr 47: Bogusław Michał Kaszewski, Szczepan Mrugała: *Wybrane charakterystyki temperatury powietrza i opadów atmosferycznych na obszarze Lubelszczyzny (1951-1990). Tom II,* Lublin 2001.

Nr 48: Zbiór publikacji: *Gleboznawstwo w badaniach naukowych i dydaktyce*, Lublin 2001.

Nr 49: Grażyna Skubisz: *Metody oceny właściwości mechanicznych łodyg rzepaku ozimego, Lublin 2001.*

Nr 50: Zbiór publikacji: *Role of soil in functioning of terrestrial ecosystems*, Lublin 2001.

Nr 51: Zbiór publikacji: *Role of soil in functioning of anthropogenic and degraded ecosystems*, Lublin 2001.

Nr 52: Zbiór publikacji: *Human induced soil-plant relations in various ecosystems*, Lublin 2001.

Nr 53: Zbiór publikacji: *Fizyka wody glebowej*, Lublin 2001.

Nr 54: Józef Horabik: *Charakterystyka właściwości fizycznych roślinnych materiałów sypkich istotnych w procesach składowania*, Lublin 2001.

Nr 55: Artur Zdunek, Krystyna Konstankiewicz: *Emisja akustyczna w badaniu procesów pękania tkanek roślinnych*, Lublin 2001.

Nr 56: Zbiór publikacji:*Gleboznawstwo w badaniach naukowych i dydaktyce.Część II,* Lublin 2001.

Nr 57: Zbiór publikacji: *Właściwości agrofizyczne środowiska glebowego,* Lublin 2001.

Nr 58: Zbiór publikacji: *Właściwości agrofizyczne materiałów roślinnych,* Lublin 2001.

Nr 59: Grzegorz Józefaciuk, Alicja Szatanik-Kloc: *Kwasowość gleby i jej wpływ na rośliny*, Lublin 2002.

Nr 60: Zbiór publikacji: *Agrofizyka na początku XXI wieku. Część I*, Lublin 2002.

Nr 61: Antoni Murkowski: *Oddziaływanie czynników stresowych na luminescencję chlorofilu w aparacie fotosyntetycznym roślin uprawnych*, Lublin 2002.

Nr 62: Zbiór publikacji: *Oddziaływanie pól elektromagnetycznych na materiały rolnicze,* Lublin 2002.

Nr 63: Zbiór publikacji: *Agrofizyka na początku XXI wieku. Część II*, Lublin 2002.

Nr 64: Józef Łukaszuk, Józef Horabik: *Wyznaczanie kąta tarcia wewnętrznego roślinnych materiałów sypkich*, Lublin 2002.

Nr 65: Jan Gliński, Ryszard Turski: *Ewolucja, zasoby i główne zagrożenia gleb*, Lublin 2002.

Nr 66: Zbiór publikacji: *Środowisko przyrodnicze Polesia - stan aktualny i zmiany. Część I*, Lublin 2002.

Nr 67: Zbiór publikacji: *Środowisko przyrodnicze Polesia - stan aktualny i zmiany. Część II*, Lublin 2002.

Nr 68: Zbiór publikacji: *Środowisko przyrodnicze Polesia - stan aktualny i zmiany. Część III*, Lublin 2002.

Nr 69: Rafał Rybczyński, Bohdan Dobrzański jr: *Fizyczne aspekty pomiaru jędrności jabłek,* Lublin 2002.

Nr 70: Zbiór publikacji: *Odpady organiczne a ochrona i produktywność agrocenozy. Część I*, Lublin 2002.

Nr 71: *Badania naukowe w Katedrze Elektrotechniki Ogólnej,* Lublin 2002.

Nr 72: Zbiór publikacji: *Zastosowania fizyki w naukach rolniczych. Część I,* Lublin 2002.

Nr 73: Zbiór publikacji: *Odpady organiczne a ochrona i produktywność agrocenozy. Część II*, Lublin 2002.

Nr 74: Józef Horabik, Marek Molenda: *Właściwości fizyczne sypkich surowców spożywczych. Zarys katalogu,* Lublin 2002.

Nr 75: Riccardo Paolo Beniccelli: *Indukcja systemu obronnego u pszenicy i pszenżyta w warunkach stresu tlenowego,* Lublin 2002.

Nr 76: Artur Boguta: *Reakcja dynamiczna nasion na obciążenie udarowe*, Lublin 2002.

Nr 77: Zbiór publikacji: *Properties of water in foods*, Lublin 2002.

Nr 78: Zbiór publikacji: *Agrofizyka na początku XXI wieku. Część III*, Lublin 2002.

Nr 79: Ryszard T. Walczak, Janusz Ostrowski, Barbara Witkowska-Walczak, Cezary Sławiński: *Hydrofizyczne charakterystyki mineralnych gleb ornych Polski*, Lublin 2002.

Nr 80: Zbiór publikacji: *Advances in plasma chemistry*, Lublin 2002.

Nr 81: Grzegorz Bowanko, Mieczysław Hajnos: *Wybrane właściwości urbanoziemów. Badania modelowe*, Lublin 2003.

Nr 82: Zbiór publikacji: *Agrofizyka w badaniach surowców i produktów rolniczych. Część I*, Lublin 2003.

Nr 83: Zbiór publikacji: *Agrofizyka w badaniach surowców i produktów rolniczych. Część II*, Lublin 2003.

Nr 84: Zbiór publikacji: *Agrofizyka na początku XXI wieku. Część IV*, Lublin 2003.

Nr 85: Zbiór publikacji: *Dolistne dokarmianie roślin*, Lublin 2003.

Nr 86–89: 2003, Vol. 1(1-4).

Nr 90: Cezary Sławiński: *Wpływ fizycznych parametrów gleby na wartości współczynnika przewodnictwa wodnego (Badania modelowe)*, Lublin 2003.

Nr 91: Pod redakcją Stanisława Radwana: *Przyrodnicze podstawy ochrony i odnowy ekosystemów wodno-torfowiskowych w obszarze funkcjonalnym Poleskiego Parku Narodowego na tle antropogenicznych przekształceń środowiska przyrodniczego*, Lublin 2003.

Nr 92: Jarosław Frączek, Janusz Kaczorowski, Zbigniew Ślipek, Józef Horabik, Marek Molenda: *Standaryzacja metod pomiaru właściwości fizyczno-mechanicznych roślinnych materiałów ziarnistych*, Lublin 2003.

Nr 93: Pod redakcją Ryszarda T. Walczaka i Wandy Woźniak: *Zastosowanie fizyki w naukach rolniczych. Część II*, Lublin 2003.

Nr 94: Jerzy Niewczas: *Metoda oceny zmian jakości materiałów rolniczych przy zastosowaniu tablic przejścia*, Lublin 2003.

Nr 95-98: 2003, Vol. 2(1-4).

Nr 99: Jerzy Tys, Wiesław Piekarski, Izabella Jackowska, Adam Kaczor, Grzegorz Zając, Paweł Starobrat: *Technologiczne i ekonomiczne uwarunkowania produkcji biopaliwa z rzepaku*, Lublin 2003.

Nr 100: Ryszard T. Walczak, Jan Gliński, Józef Horabik: *Agrofizyka i jej rola w rozwoju nauk rolniczych*, Lublin 2003.

Nr 101: Marcin Turski, Barbara Witkowska-Walczak: *Fizyczne właściwości gleb płowych wytworzonych z utworów pyłowych różnej genezy*, Lublin 2004.

Nr 102: Stanisław Grundas: *Charakterystyka właściwości fizycznych ziarniaków w kłosach pszenicy zwyczajnej Triticum aestivum L.*, Lublin 204.

Nr 103: Bogusław Usowicz, Mieczysław Hajnos, Zofia Sokołowska, Grzegorz Józefaciuk, Grzegorz Bowanko, Jan Kossowski: *Przestrzenna zmienność fizycznych i chemicznych właściwości gleby w skali pola i gminy*, Lublin 2004.

Nr 104-106: 2004, Vol. 3(1-3).

Nr 107: Mariusz Szymanek, Ignacy Niedziółka, Bohdan Dobrzański jr: *Właściwości fizyczne ziarna kukurydzy cukrowej w aspekcie jego mechanicznego odcinania*, Lublin 2004.

Nr 108: Pod redakcją Jana Glińskiego i Stanisława Nawrockiego: *Bonitacja i klasyfikacja gleb Polski*, Lublin 2004.

Nr 109: Ryusuke Hatano, Jerzy Lipiec: *Effects of land use and cultural practices on greenhouse gas fluxes in soil*, Lublin 2004.

Nr 110-112: 2004, Vol. 4(1-3).

Nr 113: Zofia Stępniewska, Grażyna Przywara, Riccardo Paolo Bennicelli: *Reakcja roślin w warunkach anaerobiozy*, Lublin 2004.

Nr 114: Ignacy Niedziółka, Mariusz Szymanek, Rafał Rybczyński: *Technologia produkcji kukurydzy cukrowej*, Lublin 2004.

Nr 115-117: 2005, Vol. 5(1-3).

Nr 118: Andrzej Bieganowski: *Metrologiczne aspekty wyznaczania potencjalnej gęstości strumienia tlenu w glebie*, Lublin 2005.

Nr 119: Urszula Kotowska, Teresa Włodarczyk: *Przemiany mineralnych form azotu w glebie nawadnianej oczyszczonymi ściekami*, Lublin 2005.

Nr 120: Pod redakcją Stefana Russela i Andrzeja I. Wyczółkowskiego: *Metody oznaczania aktywności enzymów w glebie*, Lublin 2005.

Nr 121: Pod redakcją Wenantego Olszty i Dariusza Kowalskiego: *Zintegrowany system zabezpieczeń przeciwerozyjnych i ochrony wód terenów wyżynnych intensywnie użytkowanych rolniczo*, Lublin 2005.

Nr 122: Wojciech Skierucha: *Wpływ temperatury na pomiar wilgotności gleby metodą reflektometryczną*, Lublin 2005.

Nr 123: Dorota Matyka-Sarzyńska, Zofia Sokołowska: *Właściwości fizykochemiczne utworów murszowych o różnym stopniu wtórnego przeobrażenia*, Lublin 2005.

Nr 124: Stanisław Uziak, Zygmunt Brogowski, Tomasz Komornicki : *Właściwości frakcji granulometrycznych gleb wytworzonych z różnych utworów macierzystych*, Lublin 2005.

Nr 125-127: 2005, Vol. 6(1-3).

Nr 128: Antoni Miś: *Wpływ wybranych czynników na wodochłonność i właściwości reologiczne glutenu pszenicy zwyczajnej* (*Triticum aestivum L.*), Lublin 2005.

Nr 129: Alicja Buczek: *Siedliskowe uwarunkowania, ekologia, zasoby i ochrona kłoci wiechowatej Cladium mariscus* (*L.*) *Pohl. w makroregione lubelskim*, Lublin 2005.

Nr 130: Stanisław Sosnowski: *Przyczyny powstawania uszkodzeń mechanicznych nasion fasoli podczas zbioru*, Lublin 2006.

Nr 131: Małgorzata Brzezińska: *Aktywność biologiczna oraz procesy jej towarzyszące w glebach organicznych nawadnianych oczyszczonymi ściekami miejskimi (Badania polowe i modelowe)*, Lublin 2006.

Nr 132-135: 2006, Vol. 7(1-4).

Nr 136: Jerzy Rejman: *Wpływ erozji wodnej i uprawowej na przekształcenie gleb i stoków lessowych*, Lublin 2006.

Nr 137: Małgorzata Kalicka: *Zmiany właściwości rędzin kredowych wraz z sukcesją roślinności kserotermicznej na wybranych stanowiskach Wyżyny Lubelskiej*, Lublin 2006.

Nr 138: Adam Kuczyński: *Studia nad dynamiką brązowienia i jej wykorzystaniem w ocenie świeżości miąższu jabłek*, Lublin 2006.

Nr 139-142: 2006, Vol. 8(1-4).

Nr 143: Andrzej Bieganowski: *Problematyka normalizacyjna z zakresu terminologii, badań i klasyfikacji gleb oraz zagadnień pokrewnych*, Lublin 2006.

Nr 144: Janusz Nowak, Małgorzata Bzowska-Bakalarz, Wojciech Przystupa. Pod redakcją: Janusza Nowaka: *Straty polowe w produkcji siana i kiszonek*, Lublin 2007.

Nr 145: Pod redakcją Henryka Domżała i Elżbiety Jolanty Bielińskiej: *Ocena przeobrażeń środowiska glebowego i stabilności ekosystemów leśnych w obszarze oddziaływania Zakładów Azotowych "Puławy" S.A.*, Lublin 2007.

Nr 146-148, 2007, Vol. 9(1-3).

Nr 149: Andrzej Plak: *Czynniki kształtujące zawartość i formy arsenu w glebach aglomeracji lubelskiej*, Lublin 2007.

Nr 150: Pod redakcją Ewy A. Czyż, J. Lecha Jugowara i Cezarego Sławińskiego: *Emisja gazów cieplarnianych i amoniaku w rolnictwie*, Lublin 2007.

Nr 151-153, 2007, Vol. 10(1-3).

Nr 154: Krzysztof Lamorski: *Modelowe badania pola temperatury w profilu glebowym z lokalnym zaburzeniem właściwości cieplnych*, Lublin 2007.

Nr 155: Artur Zdunek: *Instrumentalna metoda oceny wybranych cech tekstury jabłek na podstawie emisji akustycznej*, Lublin 2008.

Nr 156-158, 2008, Vol. 11(1-3).

Nr 159: Piotr Baranowski: *Temperatura radiacyjna wybranych owoców i nasion jako parametr oceny ich jakości*, Lublin 2008.

Nr 160: Stefania Jezierska-Tys, Magdalena Frąc: *Badania nad wpływem osadu z oczyszczalni ścieków mleczarskich na aktywność mikrobiologiczną i biochemiczną gleby*, Lublin 2008.

Nr 161-163, 2008, Vol. 12(1-3).

Nr 164: Jan Paluszek, Wojciech Żembrowski: *Ulepszanie gleb ulegających erozji w krajobrazie lessowym*, Lublin 2008.

Nr 165: Tomasz Słowik, Izabella Jackowska, Wiesław Piekarski: *Problemy zanieczyszczenia środowiska przez infrastrukturę transportową na przykładzie Roztoczańskiego Parku Narodowego*, Lublin 2008.

Nr 166-168, 2009, Vol. 13(1-3).

Nr 169: Pod redakcją Jacka Leśnego: *Climate change and agriculture in Poland – impacts, mitigation and adaptation measures*, Lublin 2009.

Nr 170-172, 2009, Vol. 14(1-3).

Nr 173: Pod redakcją Henryka Czachora: *Analiza czynników wpływających na zwilżalność gleb mineralnych,* Lublin 2009.

Nr 174: Wojciech Rybiński, Bogusław Szot: *Związki między agrofizyką a genetyką i hodowlą roślin zbożowych oraz strączkowych*, Lublin 2009.

Nr 175: Magdalena Ryżak, Piotr Bartmiński, Andrzej Bieganowski: *Metody wyznaczania rozkładu granulometrycznego gleb mineralnych,* Lublin 2009.

Nr 176: Alicja Szatanik-Kloc: *Zmiany właściwości powierzchniowych korzeni wybranych roślin jednoliściennych i dwuliściennych determinowane fitotoksycznością glinu i miedzi*, Lublin 2010.

Nr 177-178, 2010, Vol. 15(1-2).

ACTA AGROPHYSICA

Papers and Monographs
Instructions for Authors

The ACTA AGROPHYSICA series – Papers and Monographs, publishes reviewed papers based on original research results as well as monographs pertaining to the field of agrophysics.

Texts should be presented using font type Times New Roman CE No. 11, interline 13, with justification on both sides, paragraph indention of 0.6 cm, upper and lower margins of 5.65 cm; left and right margins of 4.1 cm, for A4 paper size.

Papers should begin with a LIST OF SYMBOLS USED (if required) – this section is not numbered.

Section and sub-section titles should be numbered with Arabic numerals and identified as follows:

- TITLES OF MAIN SECTIONS: capital letters, font size 10, left justification, line spacing above the title at 15 pts, below the title at 10 pts;
- **Titles of sub-sections**: beginning with a capital letter, font size 11, bold type, left justification, line spacing (above and below the title) 10 pts;

No division of words in titles is recommended.

Tables: All descriptions of tables (titles and headings) should be in type size 9. Full wording should be used in table titles, i.e. **Table 1.,** and the word "table" should be in bold type; no dot should be used at the end of table title; justification on both sides, e.g.:

Table 1. Composition of batters of finely comminuted sausages of the wiener type

In the text of the paper full wording should be used, e.g. Table l, and when quoting, an abbreviated form should be put in brackets – (Tab. 1). Text in table headings should begin with a capital letter. If explanations are added below the table, they should end with a dot. Tables should be composed without side border lines and internal division lines. Only thin horizontal lines defining the table beginning and end (from above and below) are to be used, as well as lines underlining the headings.

Figures: In figure captions the abbreviated form should be used **- Fig. 1.**, and no dot should be placed at the end of the caption. In the text of the paper the full word „Figure" should be used, and when quoting, the abbreviated form in brackets (Fig. 1). Figure captions are to be written with justification on both sides, e.g.

Fig. 1. Relation between Fe(II) ions (mg dm^{-3}) activated in the loess soil and the experimental time at two temperatures

In axis description in figures, the following principle is used – the description is begun with a capital letter, and units used are given in brackets, e.g. Moisture (%)

Formulae and equations: use fonts size 11, with central justification. Formulae and equations should be numbered, the numbers being put in brackets at the right margin. Line spacing above and below formulae and equations should be 0.5 cm.

Italics should be used, both in the text and in formulae, to highlight the following:

– symbols of physical values;
– single- and multi-letter abbreviations in lower (t_n, $W_{końc.}$) and upper (b^z) indexes;
– Latin names.

Straight characters are used for:

– index exponents of powers and numerical upper and lower fractions (2^2, b^3, t_2, k_2);

– abbreviations of trigonometric and hyperelliptic functions (cos, tg), symbols of vector operators (grad, div), root and integer signs and constant functional symbols (d, f, π, Σ, const, exp), symbols of units of measurement (Ω, μm), symbols of measurement units in lower indexes (h_{m}), symbols of chemical elements (Cu, k_{Fe}), symbols of physical constants (Re – Reynold's number), designation of machine and apparatus types, letters in figure numbering (Fig. 15a), all brackets.

Quoted literature references in the REFERENCES section should be arranged alphabetically, according to the authors' names. In the case of publications in a language other than English, the titles quoted should be in English (except for publications in French and German) with an indication of the original language of the publication, e.g. (in Polish), (in Russian), etc. Literature should be quoted in the text using brackets, by giving the author's name and the year of publication of the publications referenced – (Kowalski 1999) or (Kowalski and Dorn 1998). When quoting names of authors of publications with more than two authors, the abbreviated form should be used („Kowalski *et al.*"). **At one time, not more than 5 items of literature should be referenced**.

Example:

REFERENCES

Horabik J., 1994. Load distribution in a model bin as influenced by mechanical properties of wheat grain (in Polish). Acta Agrophysica, 1.

Jury W.A., Roth K., 1990. Transfer Function and Solute Movement through Soil: Theory and Applications. Birkhäser Verlag, Basel, Switzerland.

Ostrowski E.W., 1971. Evaluation of sugar beet mechanical properties (in Russian). Sacharnaja Promyszlennost, 1, 17-20.
Rampazzo N., Blum W.E.H., Strauss P., Čurlik J., 1993. Structure assessment of two agricultural soil of Lower Austria. Int. Agrophysics, 7, 47-59.
Tardieu F., 1991. Spatial arrangement of maize roots in the field. In: Plant Roots and Their Environment (Eds B.L. Mc Michael, H. Persson). Elsevier, Amsterdam, 506-514.

SI system is compulsory throughout. Units should be given as powers in round brackets – (m s^{-1})

Authors of submitted papers participate in the costs of publication. Information on the costs, as well as additional information for authors, can be found on our website:

www.ipan.lublin.pl/instytut/wydawnictwo/Actaagr

ACTA AGROPHYSICA

Rozprawy i monografie
Instrukcja dla autorów

W serii ACTA AGROPHYSICA – Rozprawy i monografie, publikowane są recenzowane opracowania oparte na oryginalnych wynikach badań oraz monografie z zakresu agrofizyki.

Tekst pracy winien być napisany czcionką Times New Roman CE nr 11, interlinia 13, wyrównanie dwustronne, wcięcie akapitowe 0,6 cm, z marginesami: górny i dolny – 5,65 cm; lewy i prawy – 4,1 cm dla formatu papieru A4.

Praca rozpoczyna się WYKAZEM WAŻNIEJSZYCH OZNACZEŃ (jeśli tego wymaga praca) – jest to rozdział bez numeracji

Tytuły rozdziałów i podrozdziałów powinny być ponumerowane cyframi arabskimi i zróżnicowane w następujący sposób:

- TYTUŁY ROZDZIAŁÓW GŁÓWNYCH: duże litery, czcionka nr 10, wyrównanie lewostronne, odstęp nad tytułem 15 pt, pod tytułem 10 pt;
- **Tytuły podrozdziałów**: z dużej litery czcionka nr 11, pogrubiona (bold), wyrównanie lewostronne, odstęp (nad i pod tytułem) 10 pt;

Nie należy dzielić wyrazów w tytułach.

Tabele: Wszystkie opisy tabel (tytuły i zawartość tabel) winny być dwujęzyczne: polskie i angielskie, pisane czcionką nr 9. Należy stosować pełny zapis w tytułach tabel, tj. **Tabela 1.** (**Table 1.**) i używać czcionki **bold** do zapisu wyrazu tabela; na końcu tytułu tabeli nie stawiać kropki; wyrównywanie dwustronne, np.:

Tabela 1. Charakterystyka badanych odmian
Table 1. Characteristics ....

W tekście używamy pełnego zapisu np. tabela 1, lub w tabeli 1, a cytując zapisujemy w nawiasie – (tab. 1).

Tekst w nagłówkach tabeli należy rozpoczynać z dużej litery. Jeżeli pod tabelą znajdują się objaśnienia należy zakończyć je kropką. Tabele należy składać bez linii bocznych i wewnętrznych. Powinny one mieć tylko cienkie linie poziome zamykające tabelę od góry i od dołu oraz podkreślające nagłówek.

Rysunki: Wszystkie opisy rysunków (podpisy, opisy osi, legendy, itp.) winny być dwujęzyczne: polskie i angielskie. Należy stosować w podpisie skrót **Rys. 1.** (**Fig. 1.**), a na końcu podpisu nie stawiać kropki. W tekście pracy należy używać pełnego wyrazu „rysunek”, a w cytowaniu skrótu (rys. 1). Podpis pod rysunkiem zapisujemy z wyrównywaniem dwustronnym, np.

Rys. 1. Zależność ilości jonów Fe(II) uruchamianych z gleby lessowej ($mg \cdot dm^{-3}$) od czasu trwania doświadczenia w dwóch temperaturach

Fig. 1. Relation between Fe(II) ions (mg dm^{-3}) activated in the loess soil and the experimental time at two temperatures

W opisach osi rysunków stosujemy następująca zasadę: zaczynamy dużą literą i podajemy jednostkę w nawiasie okrągłym, np. **Wilgotność – Moisture (%).** Jeśli opis jest długi zapisujemy wersję polską w jednej linijce, angielską w drugiej, a po niej jednostkę, np.

Udział ziaren uszkodzonych i zdolność kiełkowania
Share of damaged grains and germination capacity (%)

Wzory: należy zapisać czcionką nr 11, wyrównywanie centralne. Odstęp nad i pod wzorem powinien wynosić 0,5 cm. Wzory powinny być ponumerowane, a numery należy umieścić w nawiasach okrągłych przy prawym marginesie.

Kursywą należy wyróżnić zarówno w tekście jak i we wzorach:
- symbole wielkości fizycznych;
- jedno- i wieloliterowe skróty wyrazów w indeksach (t_n, $W_{końc.}$) lub wykładnikach (b^z);
- nazwy łacińskie.

Prostym pismem składa się:
- cyfrowe wykładniki potęg oraz cyfrowe frakcje górne i dolne (2^2, b^3, t_2, k_2);
- skróty funkcji trygonometrycznych i hiperbolicznych (cos, tg), symbole operatorów wektorowych (grad, div), znaki pierwiastka i całki oraz stałe symbole funkcyjne (d, f, π, Σ, const, exp), symbole jednostek miary (Ω, μm), symbole jednostek miary w indeksach dolnych (h_{m}), symbole pierwiastków chemicznych (Cu, k_{Fe}), symbole stałych fizycznych (Re - liczba Reynoldsa), oznaczenia typów maszyn i przyrządów, litery przy numerach rysunków (Rys. 15a), wszelkie nawiasy.

Cytowane pozycje literatury powinny być w PIŚMIENNICTWIE (REFERENCES w wersji angielskiej) uszeregowane alfabetycznie według nazwisk autorów. W przypadku artykułów pisanych w języku angielskim, tytuły cytowanych w nich prac należy podawać również w języku angielskim (z wyjątkiem publikacji francusko- i niemieckojęzycznych) z zaznaczeniem oryginalnego języka, np. (in Polish), (in Russian). Literatura powinna być cytowana w tekście w nawiasach okrągłych poprzez podanie nazwiska autora i roku wydania publikacji – (Kowalski 1999) lub (Kowalski i Dorn 1998) – w wersji angielskiej (Kowalski and Dorn 1998). Przy cytowaniu nazwisk autorów publikacji, gdy jest ich więcej niż dwóch, należy stosować skrót: (Kowalski i in. 2002), w wersji angielskiej (Kowalski *et al*. 2002). **Nie powinno się jednorazowo cytować więcej niż 5 pozycji literatury.**

Przykład:

PIŚMIENNICTWO

Horabik J., 1994. Wpływ właściwości mechanicznych ziarna pszenicy na rozkład obciążenia w zbiorniku. Acta Agrophysica, 1.

Jury W.A., Roth K., 1990. Transfer Function and Solute Movement through Soil: Theory and Applications. Birkhäser Verlag, Basel, Switzerland.

Ostrowski E.W., 1971. Opriedielienije mechaniczeskich swoistw sacharnoj swiokły. Sacharnaja Promyszlennost, 1, 17-20.

Rampazzo N., Blum W.E.H., Strauss P., Čurlik J., 1993. Structure assessment of two agricultural soil of Lower Austria. Int. Agrophysics, 7, 47-59.

Tardieu F., 1991. Spatial arrangement of maize roots in the field. In: Plant Roots and Their Environment (Eds B.L. McMichael, H. Persson). Elsevier, Amsterdam, 506-514.

Na końcu pracy powinno być streszczenie w języku polskim i angielskim (SUMMARY) – około 1 strony) wraz z angielskim tytułem pracy i słowami kluczowymi (do 5 wyrazów) oraz adresy autorów.

W liczbach dziesiętnych może być 5 miejsc łącznie z przecinkiem.

Obowiązuje system jednostek SI. Jednostki należy zapisywać potęgowo: w wersji polskiej: **($m \cdot s^{-1}$)**

Autor/autorzy zobowiązani są złożyć oświadczenie, że praca nie była publikowana w innym czasopiśmie.

Autorzy prac partycypują w kosztach jej wydania. Informacja o opłatach oraz dodatkowe informacje dla autorów znajdują się na stronie internetowej

www.ipan.lublin.pl/instytut/wydawnictwo/Actaagr

Cena: 20 zł