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Variations of Turbulent Fluxes in the Atmospheric Surface Layer According to the Presence of Cloud

Byung-Hyuk Kwon[1,*] and José Francisco de Oliveira Júnior[2]

[1]Department of Environmental Atmospheric Sciences, Pukyong National University, 599-1 Daeyeon 3-Dong, Busan, 608-737, Korea

[2]Departamento de Meteorologia, Universidade Federal de Rio de Janeiro, Av. Brigadeiro Trompowski, s/n Ilha do Fundao, Rio de Janeiro, CEP 21945-970, Brazil

구름 유무에 따른 대기표층 난류속의 변화

권병혁[1,*] · 조제 프랑시스꾸 올리베이라 주니오[2]

[1]부경대학교 환경대기과학과, 608-737, 부산 남구 대연3동 599-1

[2]히우데자네이루대학교 기상학과

요 약: 구름이 평지위의 난류속의 변화에 미치는 영향을 연구하기 위하여 스페인 빌라프리아 공항에 설치된 9 m 기상관측탑에서 얻은 역학 및 열역학 자료를 경도법으로 분석하였다. 일몰에 따른 표면 냉각은 표층 풍속을 감소시켰다. 현열속과 운동량속은 열역학적 인자 보다는 역학적 인자에 따라 증가하였고, 현열속은 열적인 조건에 영향을 받지 않았다. 구름이 존재하는 경우 전천일사량이 현열속 변화를 주도하지 못했고 대기 표층은 오히려 바람의 강도에 영향을 받았다.

주요어: 경도법, 복사, 구름, 현열속, 운동량속

Abstract: To study the effect of cloud on the variabilities of turbulent fluxes over the flat terrain, we used the gradient method to analyze the dynamic and thermodynamic data from the meteorological 9-m mast (0.75, 3 and 9 m) in Villafria airport in Spain. The decrease of the surface wind speed is governed by cooling at the surface following the evening transition. The sensible heat flux and the momentum flux are increased with the dynamic factor rather than the thermodynamic factor, and the sensible heat flux was not affected by the thermal condition. The global radiation did not play an important role in the variation of the sensible heat flux in the cloudy day, but the atmospheric surface layer was characterized rather by the wind intensity.

Keywords: gradient method, radiation, cloud, sensible heat flux, momentum flux

Introduction

The atmospheric surface layer comprises the lowest one-tenth of the atmospheric boundary layer. The sharpest variations in meteorological variables with height occur within the surface layer and, consequently, the most significant exchanges of momentum, heat and mass also occur in this layer (Arya, 1988). Characteristics of parameters, determining the evolution and daily behavior of surface layer through the surface-atmosphere interface, can be analyzed by turbulences resulting in a continuous diffusion of properties between regions. This interaction makes a random motion and mixing with another vortices inside different levels, determined by their parameterization. The atmospheric surface layer is the active link between the atmosphere and the surface of the earth. Thus its ability to transport momentum, sensible heat, water vapour and other constituents is of fundamental importance in all studies related to land surface/atmosphere as well as ocean/atmosphere exchange processes, including

*Corresponding author: bhkwon@mail1.pknu.ac.kr
Tel: 82-51-620-6288
Fax: 82-51-625-2529

parameterizations in global circulation models (Hogstrom, 1996). The turbulent structure of the atmospheric surface layer has been investigated in numerous experiments. Parameterizations of the turbulence structure over the ocean was not different from those obtained over continental surfaces and surface fluxes are closely related to the wind strength (Lenschow et al., 1980).

Absorbing gases play an important role in the atmospheric heat budget because of their maximum concentration in the atmospheric boundary layer. The cloud absorbs and reflects the longwave radiation, and moreover emits the longwave radiation. Rechou et al. (1995) found that the mixed layer top is well under the cloud layer, which translates as the clouds are decoupled from the mixed layer. Lambert and Durand (1999) showed that the mixed layer is driven by surface fluxes and is decoupled into the surface layer and the cloud layer by the stratocumulus. The nocturnal stable layer can be destroyed due to the presence of cloud heating the surface layer (Kwon, 2001). Over the oceanic Azores Current the heat budget must be balanced by a radiation divergence term, which could become large when clouds are present in the boundary layer (Kwon et al., 1998). Cloud-radiation interactions produce a temperature increase in the marine atmospheric boundary layer. During JASIN with a longwave radiation transfer model, Roach and Slingo (1979) found a heat supply 0.1-0.2℃/h to balance the heat budget. For the purpose of an examination of the cloud effect on the heat budget and the variabilities of turbulent fluxes over the homogeneous terrain, we analyzed, in this study, dynamic and thermodynamic data from a meteorological mast using the gradient method. A variation of the sensible heat flux and the momentum flux according to the global radiation will give an information for the relation between the cloud and the atmospheric turbulence in the atmospheric surface layer.

Data

A meteorological 9-m mast is operating since summer 1997 in Villafria airport (7 km away from Burgos, a 180,000 inhabitants city in Spain), 900 m over sea level, in a flat and homogeneous terrain. Three anemometers, two wind vanes, three temperature-humidity probes with a shelter, one pyranometer and three soil temperature sensors are placed on the site. A comparison of the each instrument data during the period of Jul. to Dec. 1997, with the routine observational data correspondingly, has been done. The values and variation tendency of the data are all in agreement with each other and comparatively precise and reliable. Moreover, the data sequence from Jul. 1997 to Dec. 1999 are stable, i.e. there is no obvious differences in data each year. In spring 1999, an atmospheric pressure sensor, a net radiation sensor and two soil heat flux plates were added to the instrumentation. With all this set of sensors the wind speed vector and the air temperature and relative humidity at 0.75, 3 and 9 m are obtained; solar radiation at 2 m and soil temperatures at 10, 25 and 50 cm are also measured. Data are obtained every 10 or 30 s, and every 10 min the mean values are stored in a solar-powered data logger. We used air temperature, surface wind, global radiation (Rg) and net radiation (Rn) for two days (4 and 5 October, 1997) to analyze the heat balance in the surface layer depending on the presence of cloud.

Gradient Method

In the atmospheric surface or boundary layer, direct measurements of turbulence with sophisticated fast-response turbulence instrument are most reliable to study heat and momentum. However, eddy-correlation (or even profile) measurements at ordinary weather stations are generally not available, while maximum wind gusts are often recorded routinely. The ratio of the maximum gust and the mean wind speed called gust factor is an alternative approach to get the intensity of turbulence, which was developed as a method for estimating the friction velocity and a representative roughness length from gustiness observation during strong winds (Wieringa, 1973, 1995; Beljaars, 1987). The practical advantage of determining roughness from station-measured gustiness is that only a single standard anemometer is needed.

Indirect methods of estimating fluxes from more easily measured mean winds and temperatures, for instance the bulk aerodynamic method, are most widely used to describe turbulent exchanges in the surface layer. In order to use this bulk transfer method, one needs to know the surface roughness and the surface temperature that is difficult to be determined. The surface roughness length and the friction velocity determine the structure of the neutral atmospheric surface layer. In ideal homogeneous terrain these parameters can be produced by measuring wind speed profiles in near-neutral conditions, and by application of a logarithmic wind profile. In practice this approach often fails, since wind profiles are quite sensitive to terrain inhomogeneity over fairly long fetches, and wind speed observations have limited accuracy. So the profile method is a shaky foundation for getting representative surface roughness length and friction velocity in the field (Priestley, 1959; Peterson et al., 1978). In order to minimize errors in the estimated fluxes, it is highly desirable to make measurements of mean velocity and temperature at several levels within the surface layer. However, data from two or three levels are appropriate for the gradient method or aerodynamic method, which determine fluxes from measurements of mean differences or gradients of velocity and temperature between any two heights within the surface layer, but well above the top of roughness elements.

When measurements are made at two or more heights in the surface layer, the momentum flux and the sensible heat flux can be calculated without the surface roughness and the surface temperature. The gradient method determine fluxes from measurements of mean differences of velocity and temperature between any two heights z_1 and z_2 within the surface layer, but well above the tops of roughness elements (Arya, 1988). When the difference in mean velocities and potential temperatures is $\Delta U = U_2 - U_1$ and, $\Delta\Theta = \Theta_2 - \Theta_1$ respectively across the height interval $\Delta z = z_2 - z_1$. The Richardson number can be determined approximately at the geometric mean height $z_m = \sqrt{z_1 z_2}$ assuming the logarithmic wind profile near the surface

$$Ri(z_m) \cong \frac{g}{T_0} z_m \left(\ln\frac{z_2}{z_1} \right) \frac{\Delta\Theta}{(\Delta U)^2} \tag{1}$$

The Richardson number is related to the basic stability parameter $\varsigma = z/L$ of the Monin-Obukhov (hereafter referred to as M-O) similarity theory, namely, $\varsigma = f(Ri)$

$$z_m/L = Ri(z_m)\text{, for } Ri<0 \tag{2}$$

$$z_m/L = Ri(z_m)/[1-5Ri(z_m)]\text{, for } 0 \le Ri < 0.2 \tag{3}$$

According to the M-O theory, the non-dimensional wind and temperature profiles are universal functions of z/L that are valid for the horizontally homogeneous and stationary surface layer (Monin and Yaglom, 1971):

$$\frac{\partial U}{\partial z}\frac{kz}{u_*} = \phi_m(\varsigma) \tag{4}$$

$$\frac{\partial U}{\partial z}\frac{kz}{\theta_*} = \phi_h(\varsigma) \tag{5}$$

where u_* and θ_* are the friction velocity and the scaling temperature, respectively, and k is the Von Karman constant. The flux-profile relations used in this study are generally accepted forms on the basis of the Kansas Experiment (Izumi, 1971; Businger et al., 1971):

$$\phi_h = \phi_m^2 = (1-15\varsigma)^{-1/2}\text{, for } \varsigma<0 \tag{6}$$

$$\phi_h = \phi_m = 1+5\varsigma\text{, for } \varsigma \ge 0 \tag{7}$$

Using the finite-difference approximations, the surface shear stress and sensible heat flux are given by

$$\tau_0 = \rho \left(\frac{k\Delta U}{\phi_m(\varsigma_m)\ln(z_2/z_1)} \right)^2 \tag{8}$$

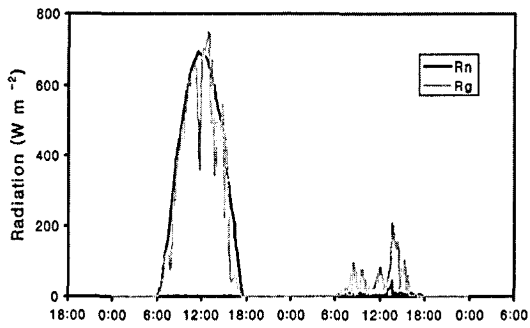

Fig. 1. Variation of the net radiation and the global radiation from 0000 LST 04 Oct. 1997 to 0000 LST 06 Oct. 1997.

$$= -\rho c_p \left(\frac{k^2 \Delta U \Delta \Theta}{\phi_m(\varsigma_m)\phi_h(\varsigma_h)\ln(z_2/z_1)^2} \right) \qquad (9)$$

Surface Fluxes

The atmospheric surface layer is approximately 10% of the atmospheric boundary layer depth nearest the interface where the height dependence of the turbulence fluxes is small and the dynamical properties are described by M-O similarity theory. Turbulent fluxes in the surface layer depend on the intensity of wind as well as the heating by the solar radiation. Therefore, surface roughness and the cloud are more important factors to study dynamic and thermodynamic characteristics of the atmospheric surface layer. We analyzed the effect of the cloud on the variability of the surface fluxes and the stability.

Figure 1 shows that it was cloudy all through the day on 5 Oct. 1997: the global radiation is less than $100\,\mathrm{W\,m^{-2}}$ until the maximum becomes about $200\,\mathrm{W\,m^{-2}}$ at 1400 LST while Rg on 4 Oct. shows general daily variation of which the maximum is about $700\,\mathrm{W\,m^{-2}}$ near 1400 LST. The variation of temperature in the surface layer responds to the solar radiation: the temperature decreases with height in the daytime and increases with height in the nighttime due to the surface heating and cooling by the shortwave radiation and the longwave radiation, respectively (Fig. 2). On 5 Oct. cloudy day, the

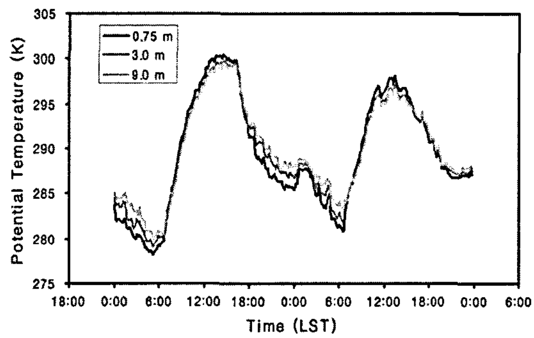

Fig. 2. Variation of the potential temperature during the same period as Fig. 1 at the three different levels (0.75, 3.0 and 9.0 m).

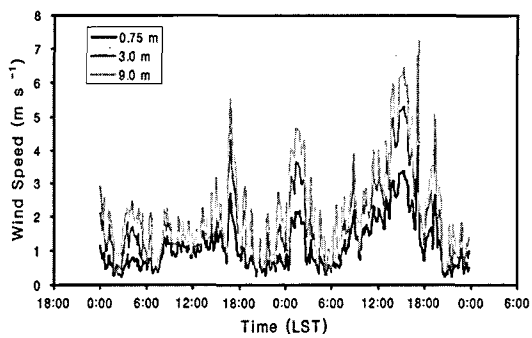

Fig. 3. Same as Fig. 2 but for variations of the wind speed.

temperatures are low by about 2 K in the daytime and high in the nighttime when the air temperature increases by longwave radiation from the cloud (Kwon, 2001). We find an incoming of the cloud after 0000 LST when the temperature increases in Fig. 2. The intensity of wind varies logarithmically with height according to power laws of which the power is about 0.4 (Fig. 3). Panofsky and Dutton (1984) described the properties of the power that varies in neutral air from 0.1 over smooth to about 0.4 over rough terrain and increases with increasing stability. The diurnal wind was stronger on 5 Oct. ($3\text{-}6\,\mathrm{m\,s^{-1}}$) than on 4 Oct. ($1\text{-}3\,\mathrm{m\,s^{-1}}$). The cloudy day was dominated by synoptic condition (low pressure) rather than by local condition around the observation post.

The surface layer is the region at the bottom of the boundary layer where turbulent fluxes and stress vary by less than 10% of their magnitude. Since the

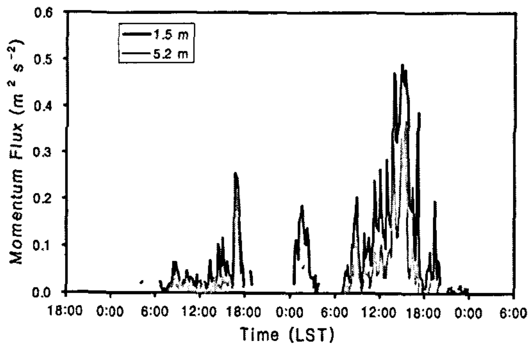

Fig. 4. Variations of the momentum flux calculated by the gradient method for two levels (1.5 m between 0.75 and 3.0 m, 5.2 m between 3.0 and 9.0 m) during the same period as Fig. 1.

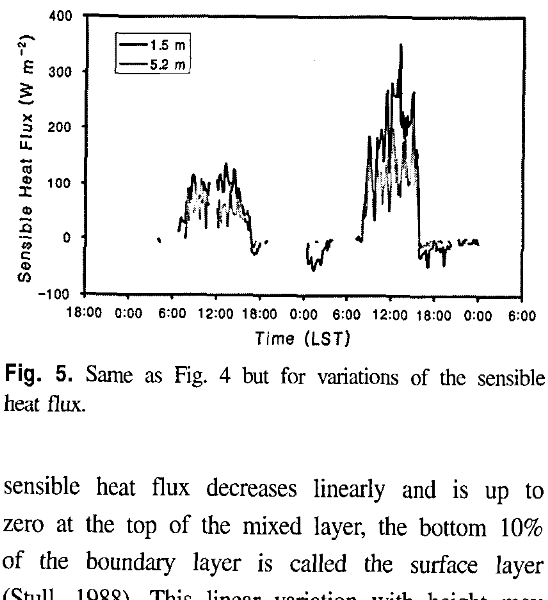

Fig. 5. Same as Fig. 4 but for variations of the sensible heat flux.

sensible heat flux decreases linearly and is up to zero at the top of the mixed layer, the bottom 10% of the boundary layer is called the surface layer (Stull, 1988). This linear variation with height may be given by normalized formula:

$$\frac{Q_H}{Q_{H0}} = 1 - C\frac{z}{h} \tag{10}$$

where Q_H is the sensible heat flux and the subscript '0' indicates the surface, and h the mixed layer height, C the coefficient depending on the entrainment at the top of the mixed layer and the intensity of the convection. Thus, over the Gulf Stream with the cold advection in the experiments *AMTEX (Agee and Howley, 1977)* and GALE (Chou and Ferguson, 1991), C is up to 1.45. Fig. 4 and Fig. 5 show the sensible heat flux and the momentum heat flux, respectively, calculated for geometric mean heights (z_m=1.5 m and 5.2 m) by the gradient method. Vertical variations of the average heat flux and the average momentum flux are already 10-20% of the maximum values at the second level in the daytime (Table 1). Thus the gradient method does not describe, in detail, vertical variations of the turbulent fluxes in the surface layer.

Lapworth (2003) determined factors governing the decrease in the surface wind speed: the surface wind speed is linked with surface cooling and gradient wind which have relationships with momentum and heat fluxes. In the case of unstable surface layer ($\varsigma<0$), turbulent fluxes are less related to the universal functions (ϕ_m and ϕ_h) depending on the stability like the equations (6) and (7). So the momentum flux depends on the wind shear while the sensible heat flux depends on the temperature shear as well as the wind shear in the equation (8) and (9). The sensible heat flux and the momentum flux increase on 5 October when the wind is stronger than on 4 October. The all peaks of the momentum flux variation are found when the wind intensity is strong, and also the decrease of the wind and the momentum flux occur at the same period around 1200 LST on 4 Oct. Over both the land and the ocean, heat fluxes of the surface depend on the thermal effect (temperature shear for the sensible heat flux and water vapor shear for the latent heat flux) rather than dynamical effect (wind

Table 1. Diurnal mean and maximum values of the momentum flux and the sensible heat flux calculated by the gradient method for 4 and 5 Oct. 1997.

	Momentum Flux (m^{-2} s^{-2})		Sensible Heat Flux (W m^{-2})	
	Mean	Maximum	Mean	Maximum
4 Oct.	0.024	0.25	25.5	150
5 Oct.	0.1	0.5	42.3	350

shear) (Kwon, 1998; Min et al., 1999). Since thermal effect in this study means the temperature difference between the two levels, which is analogous in the daytime on 4 and 5 Oct. (Fig. 2), the decrease of diurnal averaged temperatures due to the cooling by the overcast does not reduce the sensible heat flux on 5 Oct.

Conclusions

In the atmospheric surface layer fluxes were analyzed for the clear and cloudy day. The gradient method calculating the moment flux and the sensible heat flux without the surface roughness and the surface temperature is not appropriate to analyze the vertical structure of atmospheric turbulences. Since the difference of the temperature between two levels is similar during two days, the sensible heat flux is not influenced by the thermal condition. The global radiation according to the cloud does not play an important role in the variation of the sensible heat flux. The sensible heat flux and the momentum flux increase with the wind. In cloudy day the atmospheric surface layer is characterized rather by the dynamic condition.

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