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Nocturnal boundary layer profiles and measured frequency dependent influence on sound propagation

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ABSTRACT

During four evenings including one night the sound propagation up to a distance of 200 m south and north of a railway line was measured and the sound exposure level difference between the distances 25 and 200 m from a railway line was calculated. At the same time the meteorological situation was measured with a tethered balloon up to a height of 100 m. These measurements were compared with calculated wind and temperature profiles and a reasonable fit of the measured with the theoretical profiles were found.

The A-weighted sound exposure level differences were correlated with the effective sound speed gradient with respect to atmospheric stability. In the case of upwind sound propagation a difference of the A-weighted sound level in the range of 10 dB between stable and not stable (adiabatic and instable) meteorological situation was found (7 dB in the frequency range between 315 and 3150 Hz) and in the case of downwind sound propagation in the range of 3 dB(A).

The stability of the nocturnal layer is expressed with the Obukhov length L which includes (in the bulk definition) a relation of the wind speed gradient to the temperature gradient. The effective sound speed gradient includes the sum of the wind speed gradient and temperature gradient. The main result is that the description of sound propagation should be improved by use of the Obukhov length to include the stability effects of the atmosphere which is especially necessary in the case of upwind sound propagation during the nocturnal boundary layer.

1. Introduction

In the evening or morning hours, the meteorological situation changes as a result of the decreasing or increasing sun radiation which influences the temperature stratification above ground. At night the ground is cooling and with this the temperature stratification is getting stable. At the same time, the velocity and direction of wind changes which is expressed through the wind profile. To simplify the complex behaviour of the inhomogeneous atmosphere sometimes a stratified but horizontally homogenous atmosphere is used. With the horizontal stratified atmosphere the wavefront is only influenced by the vertical gradients. To combine the effect of the temperature and wind speed the effective sound speed is introduced with respect to a certain measurement point. The height dependence of the temperature and wind profiles is included in the effective sound speed gradient. In Section 3 of this paper the connection between the gradient of the effective sound speed and the measured A-weighted sound exposure level difference between the measurement points at 25 m and 200 m distance from the railway line is shown. The frequency dependent sound exposure level difference is presented for the measurement points south and north from the railway line. During two measurement periods north and south from the railway line correspond to downwind and upwind sound propagation. In the case of upwind sound propagation a remarkable difference between stable and not stable meteorology situation was found at the A-weighted sound exposure level and with this at the frequency behaviour of the sound exposure level (SEL) difference.

1.1. Introduction to the calculated and measured wind and temperature profiles

In the first part of this paper the measured temperature and wind profiles which are dependent on the height are compared with results of common used calculations for these profiles. This is useful because in the literature one finds most times a simple behaviour of the temperature and wind stratification above ground [1,3]. In this paper measurements are presented which show that during night a variety of real measured wind and temperature stratifications exist and compare well with the results of

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calculations. In Table 1 all necessary parameters to calculate height dependent wind and temperature profiles are presented. In the first part of this paper it is shown that the commonly used wind and temperature profiles are only very rough simplifications of the real existing and measured wind and temperature profile during night.

In the book of Keith Attenborough and others [1] the calculation of typical sound speed profiles are presented. This height dependent calculation of the wind speed and the temperature profile are based on the book of Panofsky and Dutton [2], but there are some differences in the use of constants which are explained later. In the book of Erik M. Salomons [3] also the calculation of the wind and temperature profiles with corresponding equations are included. The equations in the book [1] and [3] are comparable, but for simplicity the equations are referred to [1].

The aim of this part of the paper is to compare the measured wind speed and temperature profiles with the result of calculation of wind speed and temperature profiles by using Monin–Obukhov similarity theory to demonstrate the limits of the theory to describe reality specially under stable night time situations.

According to Attenborough et al. [1] the wind speed (m/s) and the temperature (°C) at height z are calculated from values at ground level (roughness length z_M, z_H and temperature at zero height T_0) and other parameters like friction velocity u_*, scaling temperature T_* and the Obukhov length L are essential parameters.

The Obukhov length L is a scaling parameter which is useful to describe the surface layer [2]. One physical interpretation of the Obukhov length is that it is proportional to the height above the surface at which buoyant factors dominate over mechanical (shear) production of turbulence [4]. According to [5] the Obukhov length is the height of the boundary layer at which the buoyant production rate equals the shear production rate of turbulence under neutral conditions.

For statically stable conditions it is suggested that the shape similarity of the temperature and wind profiles are utilised to use the (bulk definition of the) Obukhov length L [4] with

$$L = \frac{u_* \bar{\theta}(\Delta u/\Delta z)}{kg(\Delta\theta/\Delta z)} \tag{1}$$

where u_* is the Friction velocity (m/s); $\bar{\theta}$ the $\theta = T + \Gamma z$ Potential temperature (T measured in Kelvin); $\Delta u/\Delta z = (u(z_2) - u(z_1))/(z_2 - z_1)$ the Wind speed gradient between height z_2 and height z_1; k the Von Karman constant $k = 0.41$; g the acceleration due to gravity $g = 9.81\ \mathrm{m/s^2}$ and $\Delta\theta/\Delta z = (T(z_2) - T(z_1))/(z_2 - z_1)$ the Temperature gradient between height z_2 and height z_1

The term $\Delta\theta$ represents the difference of the potential temperature but in the case of small height differences for simplicity the measured temperature in °C can be used. In the following the Obukhov length was calculated with a friction velocity u_* estimated from the fit of the simulated to the measured windprofile. The temperature difference was taken between the measurement points at 13 m (z_2) and 3 m (z_1) above ground. The wind speed gradients were taken from the balloon measurements near the ground. The wind speed gradient is assumed to be constant during the up and down of the balloon (15–30 min time delay between up and down). The potential temperature is assumed to be the temperature measured in °C and converted to Kelvin (+273.15). The above definition (Eq. (1)) of the Obukhov length L represents the bulk definition as a result of the measurement of the wind and temperature gradient.

The temperature gradients $\Delta\theta$ define the surface layer if it is stable, neutral or unstable (positive, zero, negative). Therefore the Obukhov length will be a measure for stability integrating the effects of thermal and dynamical stability, which is a characteristic for the surface layer.

The reason for the change in stability mainly between day- and nighttime is the surface heatflux. From surface layer theory it is proportional to the product of the scaling quantities u_* and T_* [2].

$$H = -\rho c_p u_* T_* \tag{2}$$

H is the heat flux W/m^2; ρ the density of air $\rho \approx 1.29\ \mathrm{kg/m^3}$; c_p the specific heat at constant pressure $c_p \approx 1005$ J/kg K; u_* and T_* the u_* friction velocity, T_* scaling temperature.

The heatflux is a consequence of the radiation balance and therefore defines the situation as stable, neutral or unstable. In the proposed procedure the heatflux is used as boundary condition to estimate the scaling temperature T_*.

The height dependent measurement of the wind profile answers the question if there is a stable, neutral or unstable boundary layer [2,4]. Fig. 1 shows the variation of the wind profile on a logarithmic height scale as a consequence of stability during one measurement period of a clear night.

The curves in Fig. 1 represent a visual fit to demonstrate qualitatively the stability effect on the wind profile by using the Obukov length as the stability parameter (see Table 1). The profiles at 22:00 and 5:40 are stable stratified during night time and show deviation to higher velocities in higher levels. This is an effect of smaller turbulence elements and therefore a smoother surface layer. The morning profile at 7:20 shows the effect of an unstable stratification after sunrise. The gives stronger thermally forced turbulence and therefore deviation of the logarithmic profile to lower velocities in higher levels.

Roughness length (z_M, z_H) is a parameter which is fixed by the surface characteristic. According to the state of the surface during the measurement (e.g. long grain, bare soil and snow cover) we have chosen values according to the literature [4].

On the other hand the wind profile measurement can be used to evaluate the roughness length. The surface stress represented by the friction velocity u_* and the magnitude of the surface stress in kinematic form is u_*^2 [4]. Fig. 1 shows a value of 0.1 m/s for the night of 2nd to 3rd of July which was used then for the calculations for this night.

1.2. Calculation of the wind speed and temperature profiles

In Panofsky and Dutton [2] and Stull [4] the relation for the calculation of the wind speed is used without the shift of the height, they use z/z_M instead of $(z + z_M)/z_M$ expressed in [1]. From the mathematical point of view that means that the equations used in [1] are continuous on $z = 0$ but the following equations are not continuous on $z = 0$ because the logarithm goes to infinity on $z = 0$.

The results of Fig. 1 shows, that we have a stable boundary layer most of the time which is the reason to use the diabatic momentum and diabetic heat profile.

$$\psi_M\left(\frac{z}{L}\right) = \psi_H\left(\frac{z}{L}\right) = 5\frac{z}{L}(\text{stable stratification during night if } L > 0)$$

That finally the height dependent wind speed profile $u(z)$

$$u(z) = \frac{u_*}{k}\left[\ln\left\{\frac{z}{z_M}\right\} + \psi_M\left(\frac{z}{L}\right)\right]. \tag{3}$$

is used.

That means that the height dependent wind speed profile $u(z)$ is dependent on the height $z(m)$ and

u_* is the Friction velocity (m/s) (depends on surface roughness); z_M the Momentum roughness length (depends on surface roughness); k the Von Karman constant = 0.41; and L the Obukhov length (m)

The temperature $T(z)$ measured in °C at a height z is based on the calculation of the potential temperature θ at a certain height.