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Evaluation of local similarity theory in the wintertime nocturnal boundary layer over heterogeneous surface

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ABSTRACT

The local scaling approach was examined based on the multi-level measurements of atmospheric turbulence in the wintertime (December 2008–February 2009) stable atmospheric boundary layer (SBL) established over a heterogeneous surface influenced by mixed agricultural, industrial and forest surfaces. The heterogeneity of the surface was characterized by spatial variability of both roughness and topography. Nieuwstadt's local scaling approach was found to be suitable for the representation of all three wind velocity components. For neutral conditions, values of all three non-dimensional velocity variances were found to be smaller at the lowest measurement level and larger at higher levels in comparison to classical values found over flat terrain. Influence of surface heterogeneity was reflected in the ratio of observed dimensionless standard deviation of the vertical wind component and corresponding values of commonly used similarity formulas for flat and homogeneous terrain showing considerable variation with wind direction. The roughness sublayer influenced wind variances, and consequently the turbulent kinetic energy and correlation coefficients at the lowest measurement level, but not the wind shear profile. The observations support the classical linear expressions for the dimensionless wind shear (ϕ_m) even over inhomogeneous terrain after removing data points associated with the flux Richardson number (Rf) greater than 0.25. Leveling-off of ϕ_m at higher stabilities was found to be a result of the large number of data characterized by small-scale turbulence ($Rf > 0.25$). Deviations from linear expressions were shown to be mainly due to this small-scale turbulence rather than due to the surface heterogeneities, supporting the universality of this relationship. Additionally, the flux-gradient dependence on stability did not show different behavior for different wind regimes, indicating that the stability parameter is sufficient predictor for flux-gradient relationship. Data followed local *z*-less scaling for ϕ_m when the prerequisite $Rf \leq 0.25$ was imposed.

1. Introduction

Stable atmospheric boundary layers (SBLs) are influenced by many independent forcings, such as, (sub)mesoscale motions, which act on a variety of time and space scales, net radiative cooling, temperature advection, surface roughness and surface heterogeneity (Mahrt, 2014) enhancing the complexities and posing challenges in the study of the SBL. The fate of pollutants in the boundary layer is strongly affected by turbulence which is extremely complicated in complex terrain and over heterogeneous surfaces. Moreover, due to weak turbulence the SBL is generally favorable for the establishment of air pollution episodes. Atmospheric dispersion models, used for air quality studies, as well as high-resolution regional models use similarity scaling to model flow characteristics and dispersion in such environments.

Monin-Obukhov similarity theory (MOST) (Monin and Obukhov, 1954; Obukhov, 1946) relates surface turbulent fluxes to vertical gradients, variances and scaling parameters. The assumptions underlying MOST include stationary atmospheric turbulence, surface homogeneity and the existence of an inertial sublayer (that is, surface layer, SL). Relations between these parameters (Businger et al., 1971; Dyer, 1974) are based on several experimental campaigns conducted over horizontally homogeneous and flat (HHF) surfaces (Kaimal and Wyngaard, 1990), where the original assumptions are considered to be met. Originally, MOST was based on surface fluxes, which were assumed to be constant with height, and equal to surface values within the SL (also referred to as constant-flux layer). In the unstable boundary layer, MOST has

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been extensively studied and proven useful in relating turbulent fluxes to profiles (Businger et al., 1971; Dyer, 1974; Wyngaard and Coté, 1972). However, the applicability of MOST in the stable SL (e.g. Cheng et al., 2005; Trini Castelli and Falabino, 2013) and over complex (Babić et al., 2016; Nadeau et al., 2013; Stiperski and Rotach, 2016) and heterogeneous surfaces is still an open issue due to many difficulties when applying traditional scaling rules since MOST assumptions may not be fulfilled. Nieuwstadt (1984) extended Monin-Obukhov similarity in terms of a local scaling approach. This regime represents the extension of MOST above the SL. Accordingly, all MOST variables are based on the local fluxes at a certain height z instead of using surface values. As MOST should be valid over flat and homogeneous terrain, studies of the SBL in terms of surface layer and local scaling approaches were made over areas characterized by long and uniform fetch conditions, such as, Greenland, Arctic pack ice and Antarctica (Forrer and Rotach, 1997; Grachev et al., 2013, 2007; Sanz Rodrigo and Anderson, 2013). Forrer and Rotach (1997) concluded that local scaling is superior over surface layer scaling. This was mainly due to the fact that surface layer over an ice sheet, with continuously stable stratification, can be very shallow (<10 m). Moreover, for cases of strong stability, non-dimensional similarity functions for momentum and heat were in agreement with the results obtained from the local scaling approach. Grachev et al. (2013) examined limits of applicability of local similarity theory in the SBL by revisiting the concept of a critical Richardson number.

Even modest surface heterogeneity can significantly influence the nocturnal boundary layer (NBL) and lead to turbulence at higher Richardson numbers in comparison with homogeneous surfaces (Derbyshire, 1995). Since the earth's solid surfaces are mainly heterogeneous (at least to a certain degree), the interest in flow and turbulence characteristics over complex surfaces has increased in recent decades. Moreover, a proper representation of turbulence is particularly important for parameterization of surface-atmosphere exchange processes in atmospheric models (e.g., dispersion, numerical weather prediction or regional climate models). The turbulence characteristics have been studied through direct measurements for different complex surfaces including, complex forest sites (e.g. Dellwik and Jensen, 2005; Nakamura and Mahrt, 2001; Rannik, 1998), agricultural fields, such as, apple orchard (e.g. de Franceschi et al., 2009) or rice plantation (e.g. Moraes et al., 2005), metre-scale inhomogeneity (Andreas et al., 1998), urban areas (e.g. Fortuniak et al., 2013; Wood et al., 2010), and complex mountainous terrains (e.g. Rotach et al., 2008), addressing to both valley floors (e.g. de Franceschi et al., 2009; Moraes et al., 2005; Rotach et al., 2004) and steep slopes (Nadeau et al., 2013; Stiperski and Rotach, 2016). However, most of these studies are associated with flows over homogeneous surfaces. In recent years much effort has been put into simulations of turbulent fluxes over relatively heterogeneous surfaces using large-eddy simulations (LES, e.g. Calaf et al., 2014). Bou-Zeid et al. (2007) used LES over surfaces with varying roughness lengths to assess the parameterization for the equivalent surface roughness and the blending height in the neutral boundary layer at regional scales. Large eddy simulations of surface heterogeneity effects on regional scale fluxes and turbulent mixing in the stably stratified boundary layers were studied by Miller and Stoll (2013), Mironov and Sullivan (2010) and Stoll and Porté-Agel (2008).

The vertical structure of the atmospheric boundary layer is traditionally partitioned into a SL, an outer layer and the entrainment zone (e.g. Mahrt, 2000). The SL, in turn, is subdivided into a canopy layer (CL), a roughness sublayer (RSL) and inertial sublayer. Over surfaces with small roughness elements the latter, which corresponds to the true equilibrium layer, is often identified with SL. These concepts are less applicable over heterogeneous surfaces but for the SBL they provide, nevertheless, a useful starting point. Above very rough surfaces, such as forests or agricultural crops, the RSL has a non-negligible extension. Due to the influence of individual roughness elements on the flow within the RSL (e.g. Finnigan, 2000; Katul et al., 1999), MOST is not widely accepted. The existence of large-scale coherent turbulent structures within the RSL, which are generated at the canopy top through an inviscid instability mechanism (Raupach et al., 1996), is thought to be a reason for the failure of standard flux-gradient relationships (Harman and Finnigan, 2007).

In the scientific community substantial effort was made to address MOST in different conditions. Most of the observational studies are based on measurements from a single tower, and sometimes they result in inconsistent conclusions on the applicability of similarity theory. These inconsistencies are mostly found for studies of MOST in complex terrain (e.g. de Franceschi et al., 2009; Kral et al., 2014; Martins et al., 2009; Nadeau et al., 2013) or for small scale turbulence for which z-less scaling regime should apply (e.g. Basu et al., 2006; Cheng and Brutsaert, 2005; Forrer and Rotach, 1997; Grachev et al., 2013; Pahlow et al., 2001). The main objective of the present paper is to examine the applicability of local similarity scaling over a heterogeneous terrain influenced by a mixture of forest, agricultural and industrial surfaces, based on multi-level turbulence observations in the wintertime SBL. Many of the above mentioned studies in complex terrain are mainly characterized by homogeneous surface roughness, while studies over heterogeneous and patchy vegetation are still scarce in the literature. Additionally, this paper relates to the approach of Grachev et al. (2013), who investigated the limits of applicability of local similarity theory in the SBL over idealized homogeneous surface of the Arctic pack ice. In the present work we use their approach to distinguish between Kolmogorov and non-Kolmogorov turbulence, and consequently, to investigate whether classical linear flux-gradient relationships can be applied for non-homogeneous surfaces. The paper is organized as follows: in Section 2, we give a brief overview of the local scaling approach. In Section 3, we describe the measurement site and measurements and we provide a description of post processing procedures. Section 4 contains our results for scaled standard deviations of wind components, turbulent kinetic energy, turbulent exchange coefficients and non-dimensional wind profile. A summary and conclusions are given in Section 5.

2. Local scaling

Holtslag and Nieuwstadt (1986) presented an overview of scaling regimes for the SBL. Each of the scaling regimes is characterized by different scaling parameters. The turbulence in the SL can be described by MOST with surfaces fluxes of heat and momentum and the height z as scaling parameters. In this layer the relevant scaling parameter is the Obukhov length L (Obukhov, 1946), given by

$$L = -\frac{u_*^3}{k\frac{g}{\overline{\theta_v}}\left(\overline{w'\theta'_v}\right)_s} \quad (1)$$

where $u_* = \left(\overline{u'w'_s}^2 + \overline{v'w'_s}^2\right)^{1/4}$ is the surface friction velocity, $\left(\overline{w'\theta'_v}\right)_s$ is the surface kinematic heat flux, $\overline{\theta_v}$ is the virtual potential temperature, g is the acceleration due to the gravity, k = 0.4 is the von Kármán constant. Overbars and primes denote time averaging and fluctuating quantities, respectively.

Above the SL, the local scaling regime applies, a regime proposed by Nieuwstadt (1984). According to Nieuwstad's local similarity approach, properly scaled turbulence statistics should solely be a function of the local stability parameter $\varsigma_l = (z-d)/\Lambda$, where z is the measurement height, d is zero-plane displacement height and Λ is the local Obukhov length. Even if Nieuwstadt (1984) was not