LOCAL SIMILARITY RELATIONSHIPS IN A HORIZONTALLY INHOMOGENEOUS BOUNDARY LAYER

YAPING SHAO AND JÖRG M. HACKER

Flinders Institute for Atmospheric and Marine Sciences, Bedford Park 5042, Australia

(Received 14 August, 1989)

Abstract. Local similarity theory, an analogy to the Monin-Obukhov similarity theory, is successfully applied to airborne observations in a coastal area of South Australia. The boundary layer over this highly non-uniform surface is characterized by extensive variations in its thermal stratification and turbulence characteristics. However, the behaviour of some statistical parameters of second- and higher moments seems to be determined mainly by local forcing, while horizontal advection plays a less important role. For these parameters, local scaling is effective. It is shown that the dimensionless variances of vertical velocity and potential temperature are functions of \( z/A \) only, where \( A \) is the local Monin-Obukhov length and \( z \) is the height above ground. The dimensionless variance of horizontal velocity components is found to depend on \( h/A \), where \( h \) is the height of the boundary layer. Similarity relationships for some triple correlations are also discussed. The empirically determined local similarity relationships are found to agree with those obtained from surface-layer similarity. Finally, to illustrate the complexity of the local forcing, distributions of vertical energy and momentum fluxes, from which the local scaling parameters are derived, are shown.

1. Introduction

Similarity theory is one of the most powerful tools in describing the physical properties of the atmospheric boundary layer. In its original form, commonly called Monin-Obukhov similarity, it was applied to the surface layer only. Later, the similarity principle was extended to well-mixed layers (Deardorff, 1970), free convection layers (Wyngaard et al., 1971) and stable layers (Nieuwstadt, 1984). Similarity relationships apply not only to the mean profiles of the meteorological parameters, but also to the statistical quantities and spectral behaviour of turbulence (Kaimal et al., 1972).

However, we know of no attempt to apply the similarity principle to a horizontally inhomogeneous boundary layer, where horizontal advection should play an important role. Not only does the advection complicate the theoretical reasoning considerably, but it is also difficult to specify the advective influences from observations. To avoid these problems, most field experiments have been performed in carefully chosen homogeneous conditions. In boundary layers over non-uniform surfaces, turbulence parameters vary extensively, as reported by Raynor et al. (1979) and Hacker et al. (1988), for instance. To enable comparisons of turbulence characteristics from observations in different locations in such conditions, appropriate scaling is necessary.

Wyngaard (1973) addressed some of the problems related to a horizontally inhomogeneous boundary layer and pointed out that the most we can hope for in these cases is that local similarity holds. The study of Antonia and Luxton (1971)
who investigated (in the laboratory) a roughness step change showed evidence that some of the turbulence relations are preserved, which seems to indicate the possible effectiveness of local similarity theory. However, it is to be expected that the situation in the atmosphere is more complicated, especially due to the changing stability.

The idea of 'local scaling' can be traced back to Panofsky and McCormick (1960) who argued that the characteristics of the turbulence in the boundary layer depend mainly on its local rates of production and the height above the ground. This idea was tested by Caughey and Readings (1974) who investigated the variance of vertical wind, \( \sigma_w \), for two independent data sets. They used \( u_{*f} \) and \( \Lambda \) as scaling parameters, where \( u_{*f} \) and \( \Lambda \) are the local values of the velocity scale and the Monin–Obukhov length, respectively. Their results show a clear relationship between \( \sigma_w / u_{*f} \) and \( z / \Lambda \) for heights of up to 1000 m.

Nieuwstadt (1984) developed a more complete formulation of the local similarity theory and applied it to nocturnal observations from a meteorological mast. He found that in this case, local fluxes, shears and stability are more important than those at the surface level and that the dimensionless groups formed with local scaling parameters are functions of \( z / \Lambda \).

In this work, we try to apply local similarity scaling to a boundary layer where both surface fluxes and roughness undergo significant changes as air flows from over water to over land in a hot and dry environment. To test the effectiveness of local similarity scaling, airborne observations carried out in the coastal area of the Upper Spencer Gulf in South Australia are evaluated. The behaviour of the variances of turbulent velocity components, potential temperature and specific humidity as well as triple correlations between these quantities is investigated. From the experimental data, local similarity relationships are derived. It seems that local similarity theory does provide a tool to compare the complex turbulence characteristics at different locations in a horizontally inhomogeneous boundary layer.

2. Local Similarity Hypothesis

In general, the behaviour of a physical parameter in the boundary layer is determined by the local processes. In some cases, it can be assumed that the turbulence is in equilibrium with the surface fluxes, and local fluxes are simply related to the surface ones, so that these can be used to specify the scaling parameters. For instance, both in Monin–Obukhov similarity theory and mixed-layer similarity theory, the scaling velocity \( u_* \) (surface-layer scaling) and \( w_* \) (mixed-layer scaling) are derived from surface momentum and surface heat flux, respectively. The scaling lengths, the Monin-Obukhov length \( L \) and the inversion height \( z_i \), are also external parameters. There are, however, situations where the above assumption will or might not be valid any more and local forcing is in no simple way related to external forcing. In these cases, local scaling parameters should be derived