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Convective heat/mass transfer over complex terrain: advanced theory and its validation against experimental and LES data

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This paper presents a comprehensive revision of the classical, local theory of the convective heat mass transfer and further advancement of the recently developed non-local theory with particular attention to very rough and complex land surfaces, including mountainous landscapes. Recall that the classical theory employed the concept of the near-surface viscous layer, therefore neglected the role of the surface roughness, and strongly underestimated the surface fluxes. The key points of the new theory are (i) turbulent mixing caused by large-scale semi-organised eddies (completely overlooked in the classical theory but accounted for in modern non-local theories), (ii) interaction between large eddies and surface roughness elements up to very big obstacles such

as buildings, rocks, hills, etc. with typical heights exceeding the local turbulent-eddy scale (the so-called “large-eddy Monin-Obukhov length”).

Large-scale structures in the shear-free convective boundary layers consist of narrow strong plumes and wider but weaker downdraughts. Close to the surface they cause local “convective winds” blowing towards the plume axes. Their life-times are much larger that the overturning time scale. As a result, the convective wind shears, acting similarly to the mean-wind shears, generate turbulence in addition to its direct generation by the buoyancy forces and, by this means, strongly enhance the turbulent fluxes of heat, water vapour and other scalars near the surface. It is conceivable that the effect of large eddies should be especially strong over very rough surfaces. However, recent non-local models were insufficiently advanced to accurately reproduce the role of the surface roughness over the whole range of flow-obstacle interaction regimes.

An advanced model developed in the present paper solves this problem. It is comprehensively validated against data from measurement over different sites and also through large-eddy simulation of convective boundary layers over a range of surfaces from very smooth to extremely rough. Excellent correspondence between model results, field observations and large-eddy simulations is achieved for the whole range of the practically meaningful surface roughness lengths and boundary-layer heights. The obtained resistance and heat/mass transfer laws are recommended for practical use in meso-scale, weather-prediction, climate and other environmental models.