

Geophysical turbulent boundary layers: the nature, the theory and the role in the atmosphere-ocean system

Sergej S. Zilitinkevich

Department of Earth Sciences, Uppsala University, Sweden; Nansen Centre for Environmental and Remote Sensing / Bjerknes Centre for Climate Research, Norway

Turbulent boundary layers control the exchange processes between the atmosphere and the ocean/ice/land. The key problem of boundary-layer physics is to determine the momentum, energy and matter fluxes in a wide range of boundary-layer regimes from stable and neutral to convective. This paper presents the state of the art and modern developments in boundary-layer physics with focus on the recently recognised non-local mechanisms overlooked in the traditional theories, namely, the effect of internal gravity waves on vertical transports in stably stratified flows and the role the buoyancy-driven large-scale semi-organised eddies in convective flows. New developments are compared with experimental and large-eddy simulation (LES) data. They are motivated by urgent necessity to improve boundary-layer parameterisations in very high resolution environmental models, particularly, in the coupled atmosphere-ocean models.

Stable boundary layers (SBLs): It is common knowledge that basic features of SBLs exhibit a noticeable dependence on the free-flow static stability and baroclinicity. However, the concern of the traditional boundary-layer meteorology was almost without exception the barotropic nocturnal SBL, which develops at mid latitudes on the background of a neutral or slightly stable residual layer. The latter separates the SBL from the free atmosphere. It is not surprising that the nature of turbulence in the nocturnal SBLs is basically local, and their integral features do not depend on the properties of the free flow. The near-surface and the inner portions of these layers are well described by the Monin-Obukhov and the Nieuwstadt similarity theories, respectively. The nocturnal SBLs are sufficiently accurately modelled using traditional, comparatively simple local closure schemes.

An alternative type of the SBL frequently observed in Polar and coastal regions is the long-lived SBL, i.e. the layer in which the stable stratification is maintained day and night. Then no residual layer is observed, so that the SBL is placed immediately below the stably stratified free flow. Under these conditions, the turbulent transports of momentum and scalars even in the surface layer – far away from the SBL outer boundary – depend on the free-flow Brunt-Väisälä frequency, N . Furthermore, integral measures of the long-lived SBLs (their depths and the resistance law functions) depend on N and also on the baroclinic shear, S . In the traditional SBL models both non-local parameters N and S were overlooked. The key mechanism responsible for non-local features of the long-lived SBLs is the radiation of internal gravity waves (IGW) from the SBL upper boundary to the free atmosphere and the IGW-induced transport of the squared fluctuations of velocity and potential temperature.

The above reasoning obviously calls for a comprehensive revision of the traditional theory. In a series of papers (quoted below in References) an advanced theory has been proposed. It includes the following developments:

- *Generalised scaling for the surface layer turbulence accounting for the distant effect of the free-flow stability.* In the nocturnal SBL, it reduces to the classical Monin-Obukhov theory.
- *SBL depth formulation accounting for the free-flow stability, baroclinicity and non-steady processes.* It covers a wide range of regimes overlooked in earlier works and shows quite narrow limits of applicability of the widely used bulk Richardson number approach. For the truly neutral planetary boundary layer it yields the Rossby-Montgomery depth-scale and for the nocturnal SBL, the Zilitinkevich depth-scale.
- *Generalised SBL bulk resistance and heat/mass transfer laws accounting for the effects of the free-flow stability and baroclinicity on the A, B, C and D-stability functions.* The inclusion of the dependence on N and S resulted in essential collapse of LES data on these functions. In other words, the above laws are rehabilitated as a practical tool the SBL parameterisation. This approach has no alternative in very shallow SBLs, where traditional surface-layer flux-profile relationships become inapplicable.

The above theoretical results are verified against LES and atmospheric data. The new theory answers a number of questions, which looked puzzling until present, in particular, how well-developed turbulence is maintained in the stable surface layer at much larger Richardson numbers than the classical theory permits. It affords development of principally improved SBL parameterisations for use in a range of applied environmental models.

The physical nature of the stably stratified turbulent layers in the ocean is principally the same as in the long-lived atmospheric SBL. In both cases large eddies in the boundary layer generate IGW in the adjacent stably stratified free flow (the thermocline in the ocean or lakes), which results in the IGW-induced third-order fluxes. Thus the above new developments could be reformulated in oceanographic term and after appropriate modification (in particular including the Langmuir circulations) and validation employed in ocean modelling.

Convective boundary layers (CBLs). The most important feature of CBLs overlooked in earlier theories is the presence of large-scale semi-organised structures. In the shear-free CBLs they consist of narrow strong plumes and wider but weaker downdraughts. Close to surface they cause local “convective winds” blowing towards the plume axes. Their typical life-times are much larger than the overturning time scale. So the convective wind shears act similarly to the mean-wind shears, namely, they generate turbulence and by this means strongly enhance the turbulent fluxes of heat, water vapour and other scalars near the surface. Earlier heat/mass transfer models accounting for this mechanism were insufficiently advanced to accurately reproduce the role of the surface roughness in different flow-roughness interaction regimes. Recently, an advanced theoretical

model overcoming this drawback has been developed and validated against data from measurement in different sites over the sea and the land and also through large-eddy simulation of convective boundary layers over a range of surfaces from very smooth to very rough (Zilitinkevich et al., 2004). Excellent correspondence between model results, field observations and large-eddy simulations is achieved over a very wide range of the surface roughness lengths z_{0u} and CBL depths h : $10^3 < h/z_{0u} < 10^9$. In calm weather convection over the sea this model allows to calculate the local convective wind stress and the associated sea-surface roughness length.

The CBL depth, needed in the above model, is also required in calculation schemes for the turbulent fluxes due to entrainment at the CBL outer boundary, and in modelling of turbulent dispersion in both the lower atmosphere and the upper mixed layer of the ocean. Following earlier CBL theories, in particular those for penetrative convection regimes typical of lab experiments (Zilitinkevich, 1991), an advanced CBL-depth model is developed with due regard to physical mechanisms negligible in lab experiments but essential in geophysical CBLs, first of all, the baroclinic wind shear. The model also distinguishes between the nature of IGW generated by disturbances at the CBL-free flow interface in natural conditions and in lab experiments (where the wave lengths are restricted by the presence of side walls). The new prognostic CBL-depth equation is derived, and validated against LES and atmospheric data. Its oceanographic verification will be a subject of future work.

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