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Exploring the impact of unsteady pressure gradients and surface buoyancy on the mean wind and turbulence in the ABL

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The atmospheric and oceanic boundary layers are dynamical systems with complex characteristics that modulate their mean and turbulence responses to external forcings. These responses become particularly intractable when the forcings are unsteady. Unsteadiness primarily emanates from the variability of the large-scale mean horizontal pressure gradient and from the changes in surface heat flux, yet most previous studies have focused on steady-state flows. In this work, we conduct a suite of large eddy simulations (LES) under various stabilities and with a variable pressure gradient to elucidate the dynamics of the mean flow and turbulence under unsteady conditions.

The result indicate that the mean dynamics are quite simple in fact and can be reduced to a damped oscillator model that can be directly derived from the unsteady Reynolds-averaged Navier Stokes equations (see Momen & Bou-Zeid, 2016, Large Eddy Simulations and Damped-Oscillator Models of the Unsteady Ekman Boundary Layer. J. Atmos. Sci., 73, 25–40). The model can predict the time variability of the horizontal wind components that results from changes in horizontal pressure gradients and/or ABL stability (due to changes in surface heat flux) as simulated by the LES.

The behavior of turbulence on the other hand is more complex. Its equilibrium with the mean flow, or lack thereof, is mainly controlled by the relative magnitudes of three time-scales: the inertial, the turbulent, and the forcing variability time-scales. We show that when the forcing time-scale is on the order of the turbulence characteristic time-scale ($\tau f \approx \tau t$), the turbulence is no longer in a quasi-equilibrium state due to highly complex mean-turbulence interactions; consequently, the classic log-law and turbulence closures are no longer valid in these conditions. However, for longer ($\tau f \gg \tau t$) and, surprisingly, for shorter ($\tau f \ll \tau t$) forcing times, quasi-equilibrium is maintained.