STRATIFIED ABL EFFECTS ON URBAN WINDS

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ABSTRACT

In urban wind engineering, it is common to assume a neutrally stratified atmospheric boundary layer. While this is a valid assumption at the velocities of interest for wind loading, it may be a poor approximation for conditions relevant to other applications such as pedestrian wind and thermal comfort, airport wind-shear assessments, building natural ventilation, services exhaust reingestion and pollutant dispersion, etc.

For urban wind comfort analysis, winds between 1 and 10 m/s are generally governing. Under these conditions, atmospheric boundary layer (ABL) stratification can be strong, and have a large influence on pedestrian level winds. This is particularly relevant for thermal comfort assessments, which often assume linear scaling of fast and neutral winds down to velocities as low as 1 m/s. Such assessments may consider weather extremes such as a particularly hot summer day with low winds, for which the assumption of neutral winds may be a significant source of error.

To examine the ABL stratification that might be expected for this application, a year of data has been obtained from the Bureau of Meteorology's ACCESS numerical weather prediction model for several Australian cities. The relationship between wind speed and Obukhov length has been plotted to examine the distribution of Obukhov lengths at velocities of 10 m/s and lower, the velocity range relevant to many urban wind applications. Based on the ACCESS data, winds can be considered exclusively neutral above approximately 6 m/s in the stable case, and 9 m/s in the unstable case.

To examine the sensitivity to ABL stratification, a computational wind model is developed for a simple pedestrian comfort case. Ground level wind speeds and turbulent kinetic energy are assessed for stable and unstable stratified inflow, and compared against the neutral case. For the case of a single high-rise building, stable stratification was found to produce significantly higher ground level accelerations for the same reference velocity. Conversely, ground level winds during unstable stratification are slower than the neutral case.

This work thus provides an indication of the consequences of neglecting atmospheric stratification when considering urban wind effects.

THE STRATIFIED ATMOSPHERIC BOUNDARY LAYER

During the course of a day, the atmospheric boundary layer (ABL) undergoes a diurnal cycle. The ground and ocean collect and radiate thermal energy more rapidly than the air above. As the sun rises in the morning, the ground heats up resulting in a layer of warm and lower density air than that above. This scenario is 'unstable' as the resulting buoyancy gives rise to convective motions, increasing the turbulence and hence mixing within the ABL. A side effect is that the depth of the ABL significantly increases, to the order of kilometres above ground level. As the sun sets the inverse occurs, where air at low level rapidly cools, giving rise to an ABL with 'stable' stratification. Under stable conditions, vertical motions and hence turbulence are suppressed, and the depth of the boundary layer shrinks significantly. The strength of the ABL stratification is governed by the ratio of mechanical and buoyant production of turbulence, expressed as the Obukhov length, L:

$$L = \frac{\theta U_*^3}{\kappa \cdot g \cdot \overline{w'\theta'}}$$

Where θ is the potential temperature, U_* is the friction velocity, κ is Von Karman's constant of 0.41, g is gravitational acceleration, and $\overline{w'\theta'}$ is the kinematic temperature flux. The Obukhov length is often used to categorise the stratification of winds as shown in table 1 (e.g. Pena Diaz et. al. 2009).

Table 1. Stability categories by Obukhov Length

Obukhov Length [m]	Stability Class	
$10 \leq L \leq 50$	Very Stable	(VS)
$50 \leq L \leq 200$	Stable	(S)
$200 \leq L \leq 500$	Near-Neutral Stable	(NNS)
$\|L\| \geq 500$	Neutral	(N)
$-500 \leq L \leq -200$	Near-Neutral Unstable (NNU)	(NNU)
$-200 \leq L \leq -100$	Unstable	(U)
$-100 \leq L \leq -50$	Very Unstable	(VU)

By assuming a constant shear stress surface layer, Monin-Obukhov similarity theory (MOST) can be used to provide the velocity profile for a stratified ABL:

$$U(z) = \frac{U_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\right]$$

Where Ψ_m is a MOST stability function for momentum. There are several different formulations in the literature for the MOST stability functions, but in the sections below the profiles of (Panofsky and Dutton 1984) are adopted for comparison with the simulation.

The stratified ABL profiles for velocity and turbulence can vary significantly from the neutral winds which are typically assumed for urban wind problems. What isn't clear is to what extent these profile differences affect urban winds, and in what conditions it may not be appropriate to simply assume neutral stratification. A common justification is that "strong winds are neutral", but many urban wind applications are not only concerned with strong winds (e.g. pollutant dispersion, pedestrian wind and thermal comfort, etc). What wind speed is required for this assumption to be valid?

FREQUENCY OF STRATIFIED WINDS

To examine the frequency at which stratified winds occur, data have been collected from the Bureau of Meteorology's (BoM) Australian Community Climate and Earth-System Simulator (ACCESS) (Puri et. al. 2013). ACCESS is a numerical weather prediction (NWP) model, which computes global weather with a grid resolution of about 12.5km, with a series of nested grids at higher resolution of 1.5km around major Australian cities. For each hour of 2022, velocity and temperature fields are collected for the 0-hour forecast (the point at which the model is updated to assimilate observations, which serves as the new initial condition for the model forecasting). For several Australian cities, the model fields are averaged across the central business districts (CBD), and the Obukhov length is then calculated. For each city, the median and minimum magnitude Obukhov length across the range of velocities is determined and plotted in figure 1. Note that for the low velocities there are events which appear to have stratification much stronger than the strongest classifications, but these are more likely an indication of MOST not being appropriate for calm winds, than representative of the real stratification.

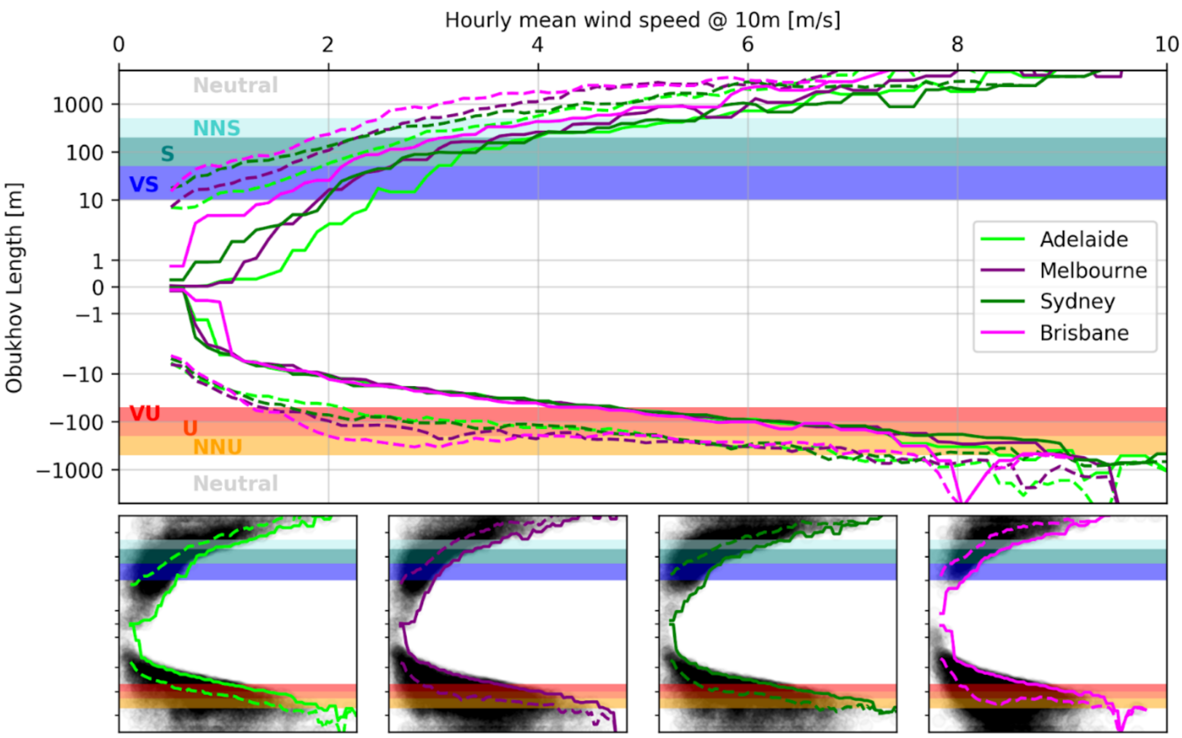

Figure 1. Median (dashed) and strongest stratification (solid) Obukhov lengths for four Australian cities in 2022.

There is a clear trend toward neutral winds with increasing velocity. In general, Adelaide experiences the strongest stratification of the four cities, while Brisbane experiences the weakest. For all cities, median unstable winds are at least within the NNU category up approximately 7 m/s. For stable winds there is more variation by city, where the median stratification of Adelaide winds is similar to the maximum stratification of Brisbane winds.

Below 2 m/s, there are a large number of events which are more strongly stratified than the maximum stability categories. Rather than indicating an issue with the categories themselves, it is likely that in this regime the assumptions of MOST are no longer appropriate, and the extreme stratification is non-physical.

Based on the ACCESS data for these cities, winds can be considered as exclusively neutral at speeds above ~6 m/s in the stable case, and ~9m/s in the unstable case. However it is important to note that this data is for the CBD of each city, where stratification is expected to be at its weakest due to the increased surface roughness (urban heat island and albedo may also reduce stratification, particularly in the stable case). Additionally, the Obukhov length at a particular location is based on the local friction velocity and heat flux, missing the influence of upstream stratification (particularly important when the city is downwind of the ocean). Finally, it should be noted that these data are based on an NWP model, and not observations. NWP models use simple parameterisations for surface fluxes, which cannot account for the complex flow around dense urban environments.

COMPUTATIONAL MODEL

To test the sensitivity to stratification for a common wind engineering application, a computational model is developed for stratified wind over a building, to examine the influence on pedestrian wind comfort. Based on the distribution of velocities and Obukhov lengths, a 3 m/s wind at 10m height has been simulated for neutral conditions, and with Obukhov lengths of 100 m and -100 m. The unstable case is therefore representative of a 3 m/s wind with median unstable stratification in Adelaide and Sydney, while the stable case is representative of a 3 m/s wind with peak stratification in Sydney and Melbourne.

The simulation is carried out in OpenFOAM, making use of a buoyant steady-state solver and using the $k\omega SST$ turbulence model. The surface roughness is set to a roughness length of 0.2 m, corresponding to suburban surrounds. To simulate the stratified ABL, a precursor simulation is conducted for a cyclic empty domain. The temperature field is constrained to a MOST profile below 1000 m, while a capping inversion is applied above by applying an increasing potential temperature of 8 K/km. Newtonian relaxation is used above the ABL to force the geostrophic wind towards 10 m/s. For the stable case, the inversion is instead applied from 200 m up, as a 1 km tall boundary layer is not realistic for such stable stratification. A pressure gradient is then applied to the cyclic domain, tuned to produce a 3 m/s velocity at 10 m height. The resulting profiles of velocity and turbulence are shown in figure 2. The turbulence shows the desired properties, closely matching the MOST profiles near the surface, before decaying to zero at the top of the ABL. While there are no analytical profiles for stratified flow in these conditions (i.e. a non-constant shear stress with stratification), the pressure driven profile of (Richards and Norris 2015) has been provided for comparison with neutral conditions.

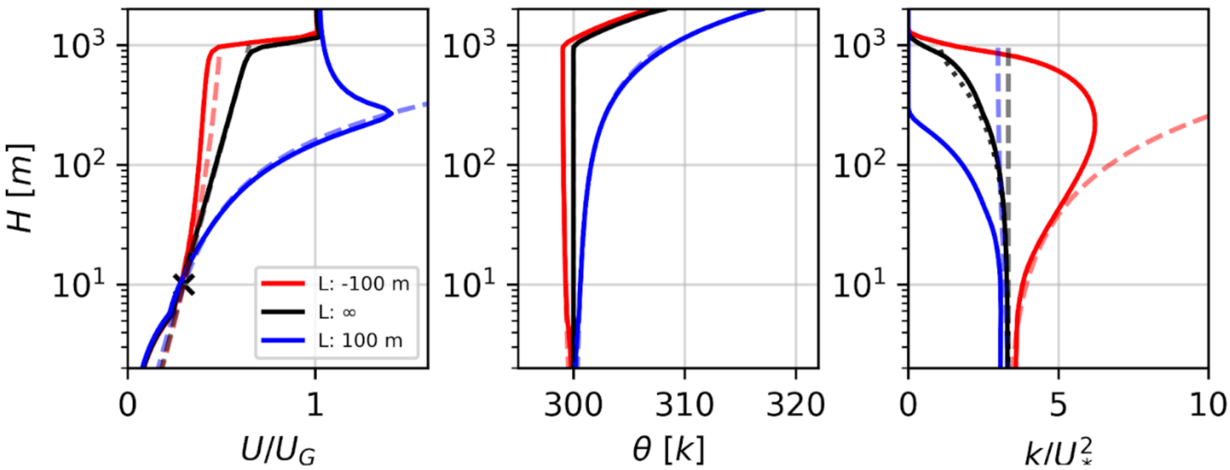

Figure 2. Simulated (solid), MOST (dashed), and pressure driven (dotted, Richards and Norris 2015) inflow profiles.

These inflow profiles are then mapped to a successor domain, to solve for flow over a high-rise building. The building is 30 m x 30 m horizontally, and 100 m in height. The building model is run until convergence of the steady state model, and the resultant velocity and turbulence fields are plotted at 2 m height in figure 3.

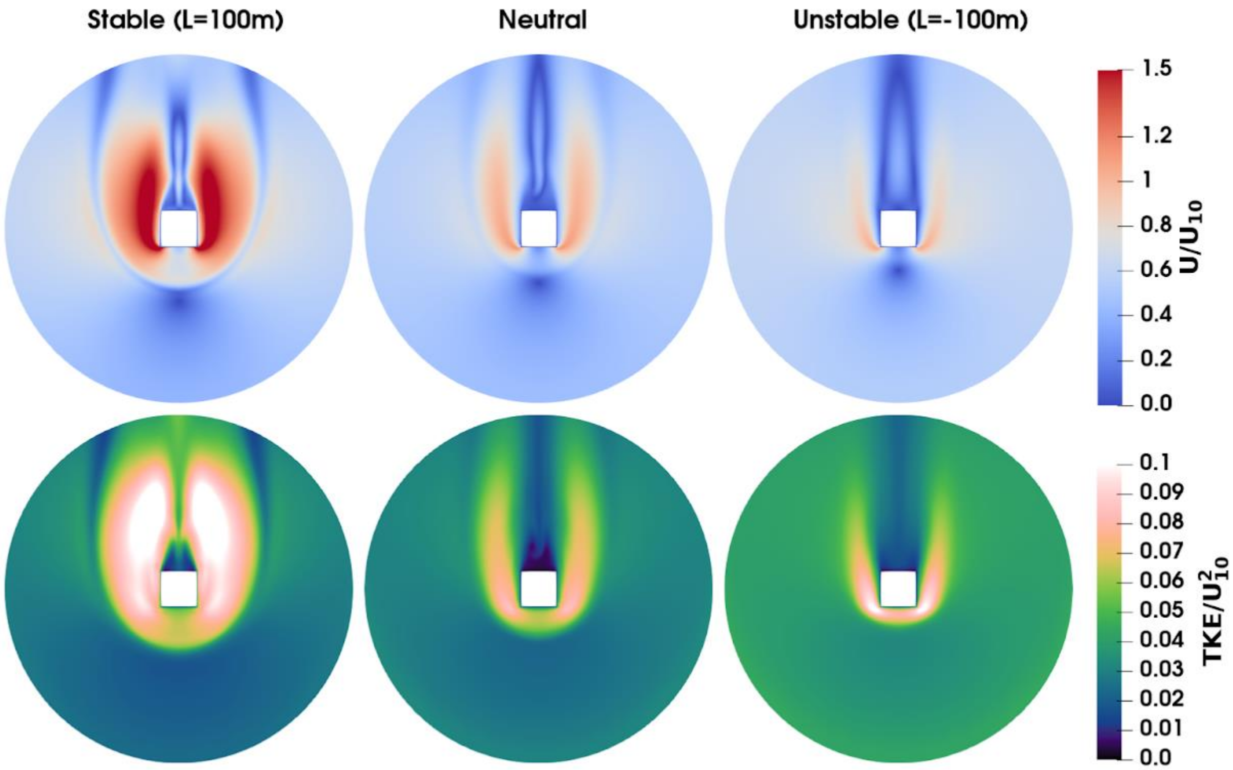

Figure 3. Simulated ground level velocity and TKE

It is clear that the stratification of the ABL profile can have a significant effect on the ground level wind environment around an isolated high-rise building. Compared to neutral winds of the same reference velocity, stably stratified winds produce much faster pedestrian-level winds, across a larger area of influence. While the 10 m velocities are the same the stable inflow is much faster at the building roof level, resulting in stronger downwash.

The unstable case is generally the inverse of the stable case, with a lower mean velocity across the height of the building resulting in significantly reduced acceleration of ground level winds, and a faster wake recovery.

For a pedestrian wind comfort study of this building, neglecting ABL stratification would likely be conservative when examining ground level winds, as these studies generally consider winds during daytime hours and place less importance on nocturnal winds. However, stable stratification can occur during occupied hours, particularly in the evening after sunset. This is critical for rooftop bars and terraces, for which wind speeds can be significantly higher during stably stratified winds.

While neglecting unstable stratification in this case may be conservative for a pedestrian comfort study, similar CFD models are often also used for thermal comfort studies. For such studies, adequate street level ventilation during warm weather and low wind conditions is a key design consideration. By considering only neutral winds, the level of ventilation at street level during lower wind speeds may be significantly overestimated.

It should be noted that these conclusions are likely to differ when considering multiple buildings of similar height. Studies of stratified flow over arrays of identical height cubes (e.g. Uehara et. al. 2000, Kanda and Yamao 2016) have shown street level velocities to be much lower during stable winds, while the increased mixing during unstable stratification promotes the transport of momentum into the urban canyon. The relationship between stratification and ground level winds is thus likely to depend on the density and heights of the buildings under consideration. For a building much taller than its surroundings, stable stratification is likely to produce the faster ground level winds. For more closely spaced buildings of similar heights, ground level acceleration may be higher during unstable winds.

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