Flushing of a stably stratified urban canyon

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We present results of a series of salt bath experiments that examine the flushing of a dense pollutant from a model urban canyon. Results are presented for a range of Richardson numbers (based on the canyon height and pollutant density), canyon aspect ratio (canyon width to height ratio), and upstream boundary layer characteristics. Both transient and steady-state experimental results are presented.

The transient experiments were used to measure the time varying stratification in an initially well mixed canyon that is being flushed by a flow over the top of the canyon. When the ambient flow is first turned on there is an initial deflection down of the density interface at the leading edge of the canyon. The vertical extent of this deflection decreases with increasing Richardson number (Ri) and is independent of the canyon aspect ratio for aspect ratios less than two. After the initial deflection a vortex forms at the upstream end of the canyon which travels across the top of the canyon and is then deflected down into the canyon. The depth of penetration of this vortex decreases with increasing Ri. This vortex is then the primary driver of flushing.

Three flow regimes are observed during these tests. For low Ri the canyon remains relatively well mixed and the pollutant concentration decays exponentially with time. For intermediate Ri the canyon exhibits a stable stratification with a relatively uniform buoyancy gradient throughout the canyon. For Higher Ri a two-layer stratification is observed with a sharp density interface separating the layers. The transition Richardson number that separates these regimes varies with canyon aspect ratio. The initial decay rate is a decreasing power law function of the Ri for larger Ri and approaches a constant as Ri approaches zero. The maximum mixing efficiency is observed to occur near the transition from the continuously stratified to the two-layer regime. The decay rate decreases with decreasing canyon aspect ratio as the primary vortex becomes laterally constrained by the canyon walls, inhibiting its vertical penetration.

A series of steady-state tests were also run in which dense salt solution was continuously added to the canyon. Once a steady-state flow is established the rate of flushing is equal to the rate of injection of dense fluid and can, therefore, be measured directly. The same flow regimes were observed as described above for the transient experiments. The measured flushing rates were the same as measured during the transient experiments. However, the steady-state experiments did indicate that there are two mixing processes at work. There is a skimming flow, that removes dense fluid by scrapping it from the top of the density interface, and interfacial mixing that mixes fresh ambient water down into the dense lower layer. Both of these processes were parameterized as functions of the flow Ri.

Finally, a series of experiments were conducted to examine the influence of ambient turbulence on the flushing rate. Transient experiments were run for a square canyon with three different upstream surface roughness heights and a range of Ri. The different upstream morphologies altered the turbulence intensity (Ix) profile in the upstream boundary layer. For a given Ri, the initial decay rate was found to be independent of Ix. However, after some time the measured decay rates would diverge with Ix. For larger Ix the decay rate would increase while for lower Ix the decay rate would decrease. This suggests that there is a transition in mixing process away from one dominated by the mean flow and the primary vortex to one controlled by small scale turbulent nibbling. Effectively, the mean flow's ability to flush becomes exhausted and ambient turbulence then drives the flushing. Prior to that, the mean flow dominates and Ix plays no significant role. It is interesting, however, that there are cases in which, after this transition, the decay rate increases indicating that, at earlier stages, the mean flow suppresses the role of ambient turbulence in the mixing.

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