On the Sensitivity of Urban Flow and Ventilation to Time-Dependent Inflow Perturbations

Guangdong DUAN[a] (g.duan@my.cityu.edu.hk), Keith NGAN[a] (keith.ngan@cityu.edu.hk), Ka Wai LO[b]
[a]School of Energy and Environment, City University of Hong Kong, Hong Kong SAR; [b]Environmental Protection Department, Hong Kong SAR

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1. Introduction

- Urban flow and turbulence are driven by unsteady mesoscale forcing. Since building-resolving computational fluid dynamics (CFD) models typically employ steady Dirichlet boundary conditions or forcing, the accuracy of numerical simulations could be limited by the neglect of perturbations.
- An important question for coupled urban-mesoscale modelling is the sensitivity to the time-dependent inflow. Small perturbations to the initial conditions can yield O(1) errors within a finite time **[1]**, but the effects of continuous forcing could be rather different.
- The effects of time-dependent inflow perturbations on the flow and ventilation over a unit-aspect-ratio street canyon are investigated using the large-eddy simulation (LES) model, PALM **[2]**.
- Synthetic inflow perturbations are incorporated via nudging. Coupling with mesoscale winds **[3]** is also possible, but elucidation of the basic physical mechanisms is more complicated.

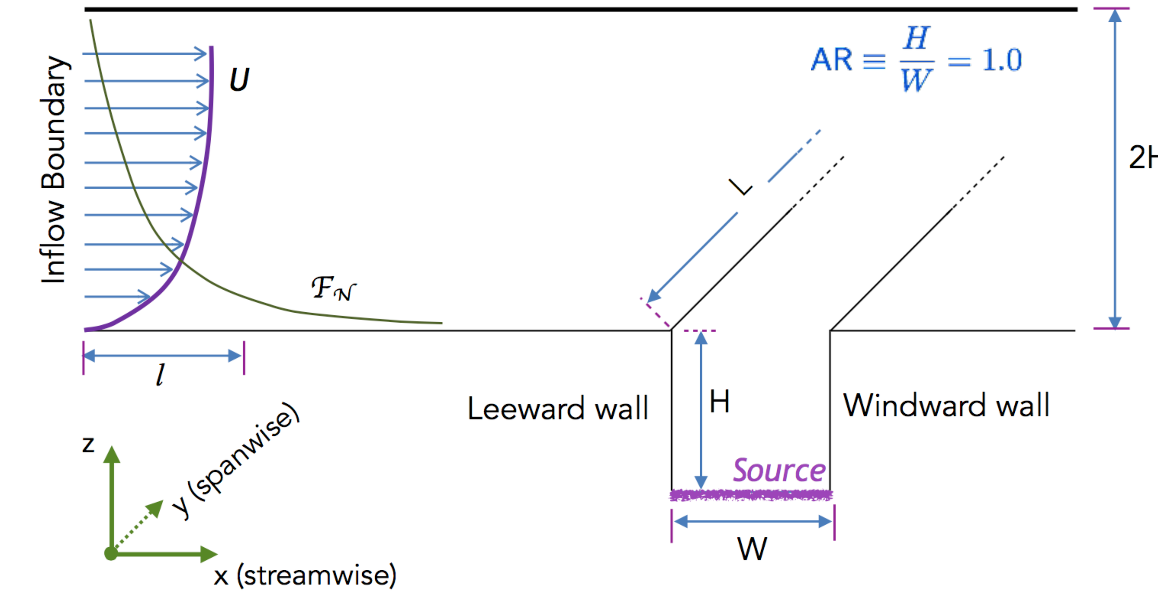


Fig.1 Schematic diagram of the computational domain.

$$\dot{X} = F(X,t) + \mathcal{F}_N$$

$$\mathcal{F}_N = \frac{1}{T_0}(X - X_0)$$

$$X_0(z,t) = U_{LS}(z)[1 + \varepsilon \sin(\omega t)]$$

2. Flow Structure and Turbulence Statistics

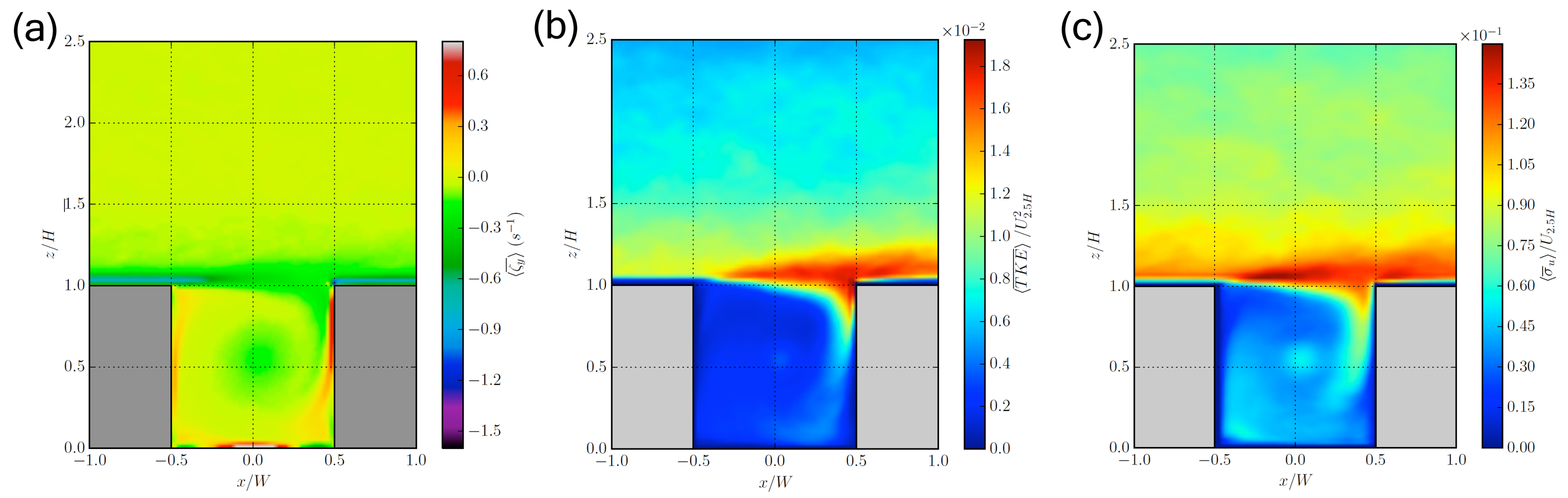


Fig.2 Dynamical fields for the unperturbed case. (a) Spanwise vorticity ζ_y; (b) TKE; (c) turbulence intensity of the streamwise velocity u.

The spatial structure is largely insensitive to the inflow perturbations.

3. Dispersion and Ventilation

For a perturbation with period T=300s, the concentration within the central vortex is about 16% higher.

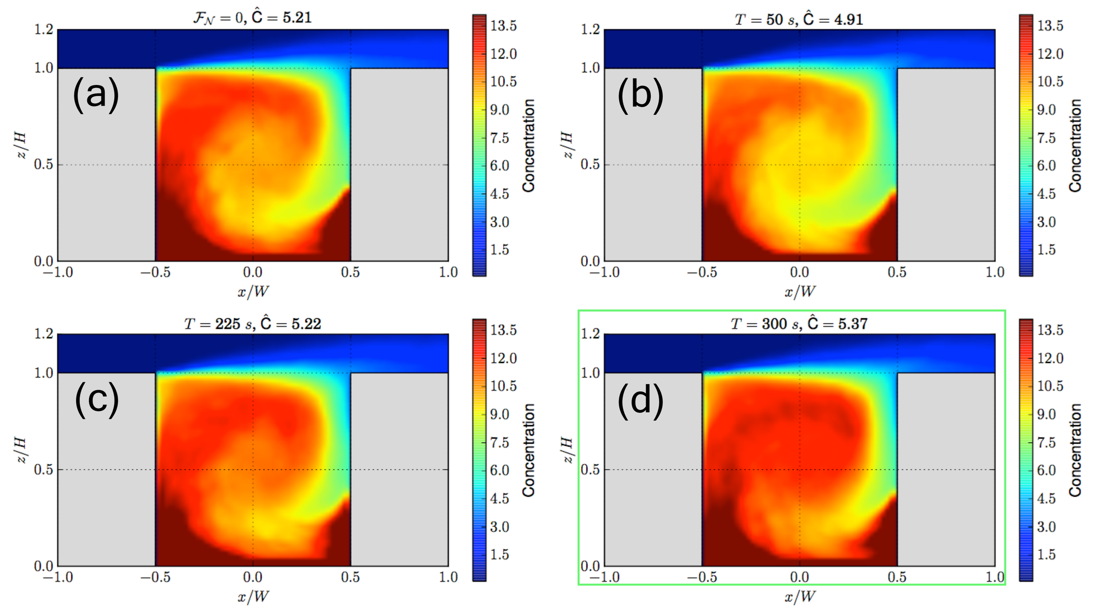


Fig.3 Concentration fields. (a) Unperturbed; (b) T=50s; (c) T=225s; (d) T=300s.

Ventilation improves by approximately 10% compared to the unperturbed case.

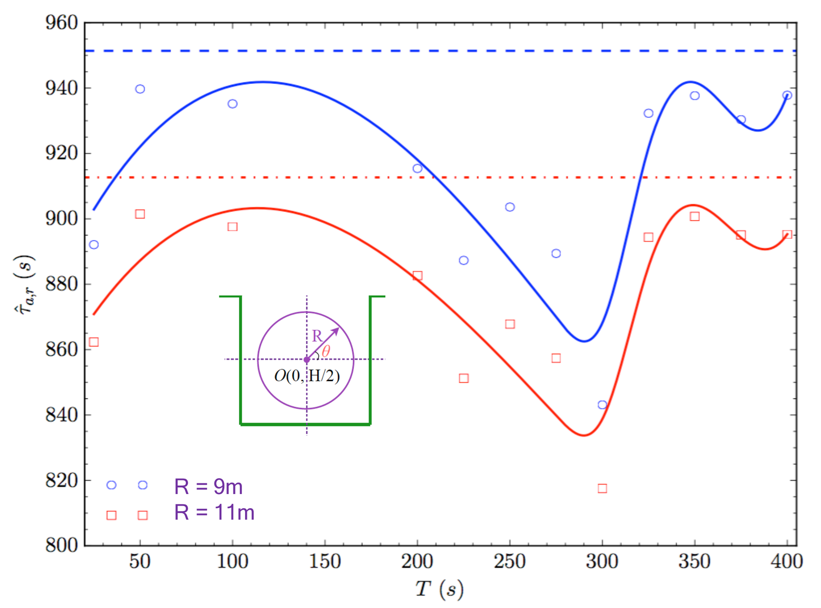


Fig.4 Mean tracer age **[4]** within the nominal vortices of radius R=9m and 11m.

4. Error Statistics

Following analyses of predictability in homogeneous turbulence and atmospheric science, the error kinetic energy and relative error may be used to assess the impact of the inflow perturbation. Errors were diagnosed by identical-twin experiments.

- Time-dependent nudging induces additional errors with respect to initial-condition (IC) perturbations [1].

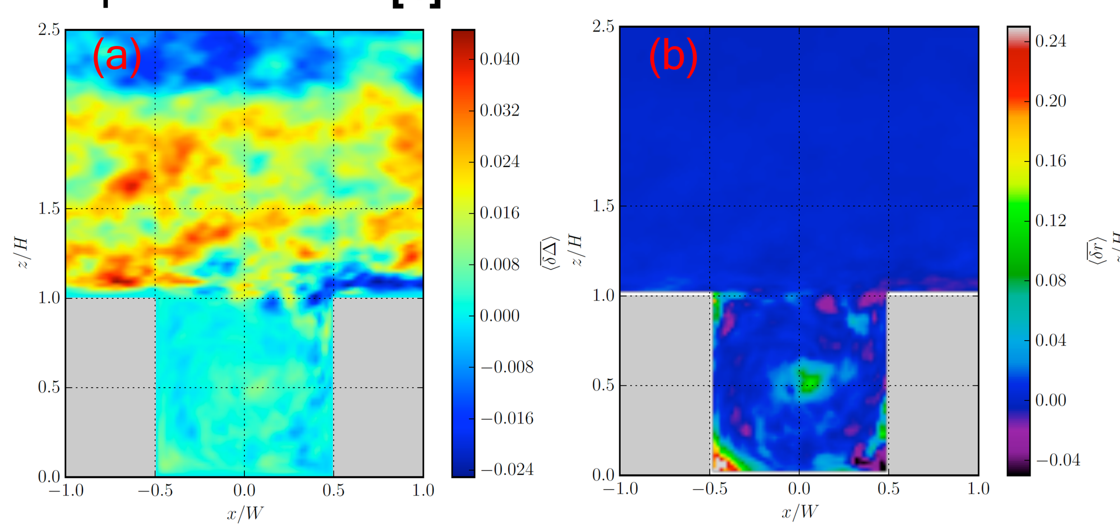


Fig.5 Differences with respect to the IC perturbation. (a) Deviation in the error kinetic energy; (b) deviation in the relative error.

- The error fields closely resemble those of IC perturbations. Highest sensitivity is seen over corners and the central vortex.

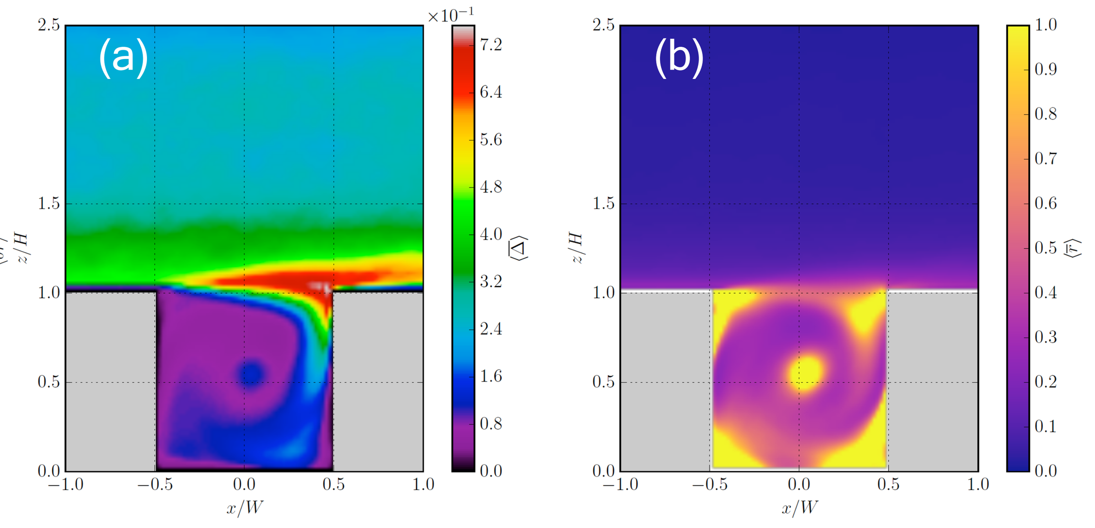


Fig.6 (a) Error kinetic energy; (b) relative error for T=300s.

- Sensitivity remains strongest for 225s≲T ≲300s.

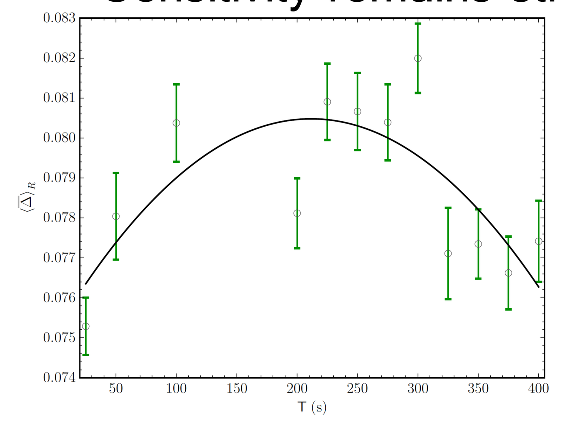


Fig.7 Error kinetic energy within the nominal vortex of radius R=9m.

- Maximization of the sensitivity matches the timescales for the inner and outer vortex cores.

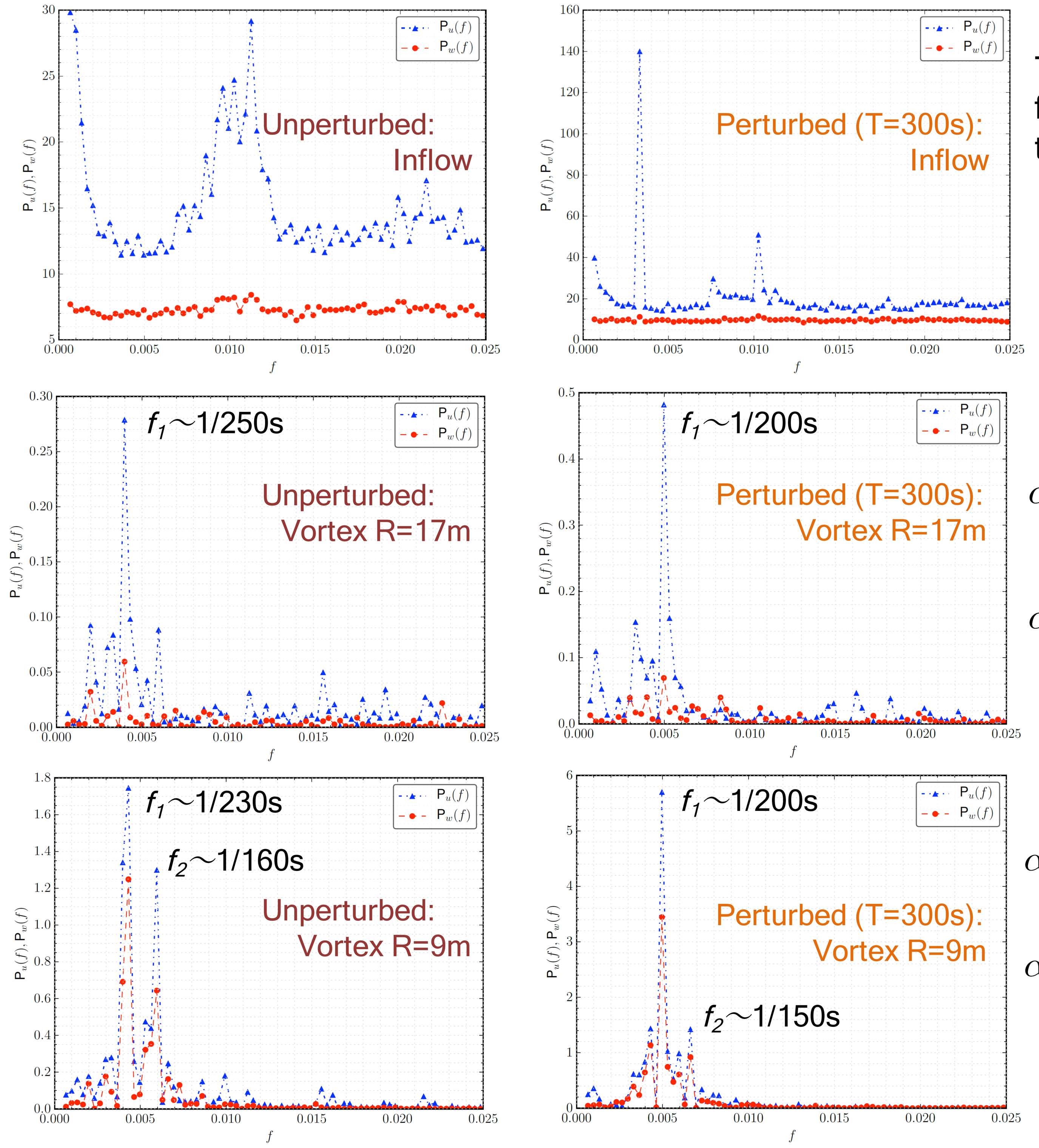
R (m)	T_{eddy} (s)
23.5	280
9.0	110

Table 1 Eddy circulation timescales for R=23.5m and R=9m estimated via:

$$T_{\text{eddy}} = \frac{2\pi R}{V_\theta}.$$

5. Physical Mechanisms

If linear dynamics are applicable within the canyon **[5]**, one may expect an enhanced response when the perturbation frequency matches that of the mean canyon circulation. This leads to large departures from the unperturbed motion.



The peak at the perturbation frequency does not dominate the energetics (~10%P_{total})

$$\alpha_u(f_1) = \frac{P_{\langle u\rangle R}|_T}{P_{\langle u\rangle R}|_{\mathcal{F}_N=0}} = 1.71$$

$$\alpha_w(f_1) = \frac{P_{\langle w\rangle R}|_T}{P_{\langle w\rangle R}|_{\mathcal{F}_N=0}} = 1.16$$

$$\alpha_u(f_1) = 3.26, \ \alpha_u(f_2) = 1.08$$

$$\alpha_w(f_1) = 2.72, \ \alpha_w(f_2) = 1.38$$

Fig. 8 Frequency Spectra of the (left panel) unperturbed and (right panel) perturbed cases of T=330s. (First row) inflow; (second row) vortex core of R=17m; (last row) vortex core of R=9m.

6. Summary

Flow and turbulence statistics within a street canyon depend weakly on the timescale of inflow perturbations. Error kinetic energy is maximised for perturbation periods comparable to the dominant timescales of the canyon flow. Spectral analyses indicate that a resonance occurs between the inflow perturbation and the mean canyon circulation. Results should generalise to other canyon geometries so long as the error dynamics are approximately linear and the mean flow is dominated by a coherent canyon circulation with distinct characteristic timescales.

References

[1] Lo, K.W. & Ngan, K., 2015. Boundary-Layer Meteoro. **[2]** Maronga, B., et al., 2015. Geosci. Model Dev. **[3]** Yamada, T., 2004. Computational Fluid Dynamics J. **[4]** Lo, K.W. & Ngan, K., 2015. Atmos. Environ. **[5]** Ngan, K. & Lo, K.W., 2016. J. Appl. Meteorol. Clim.