Extremely causal events of turbulent channel flow

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This study examines causally important events in turbulent channel flow by tracking the evolution of spatially localized perturbations. The methodology follows the causal analysis of 2D HIT by Jiménez [1], and was recently extended to 3D HIT by Encinar [2] Direct numerical simulation of turbulent open channel flow at $Re_\tau = 609$ is used, with a domain size of $l_x \times l_y \times l_z = \pi h \times h \times \pi h$, where h denotes channel height. The fully developed flow is initially perturbed by replacing the velocity in a cubic cell with its $x-z$ average. The cell size is varied from $l^+_{cell} = 25$ to 150, and the bottom height of the cell, y^+_{cell}, is varied from 0 to 300. Causal significance is measured by the growth of velocity perturbation energy, $\sigma = log(\Delta q(t)) - log(\Delta q(0))$, where $\Delta q = \int_\Omega (u_{per_i} - u_{org_i})^2 dV$ and Ω stands for the flow domain. This experiment is repeated many times with changing perturbed location and snapshot. In total, 29520 experiments were conducted.

The time at which causal significance most diverges, t_{sig}, is found to be proportional to y_{cell}. Characteristic flow features of causally significant and irrelevant cells at t_{sig} depend on the cell height. For perturbations attached to the wall, mean shear in the cell distinguishes significant/irrelevant perturbations. For those detached from the wall, significant/irrelevant perturbations tend to be located in sweep/ejection. The relation of those flow features with causality can be explained by the local shear experienced by the perturbations. Conditional flow around significant/irrelevant cells of detached perturbation turned out to be a larger-scale sweep/ejection lying upon smaller-scale ejection/sweep beneath (fig. 1). Interestingly, the one for irrelevant perturbations is opposite of the typical conditional tall attached sweep-ejection pairs[3].

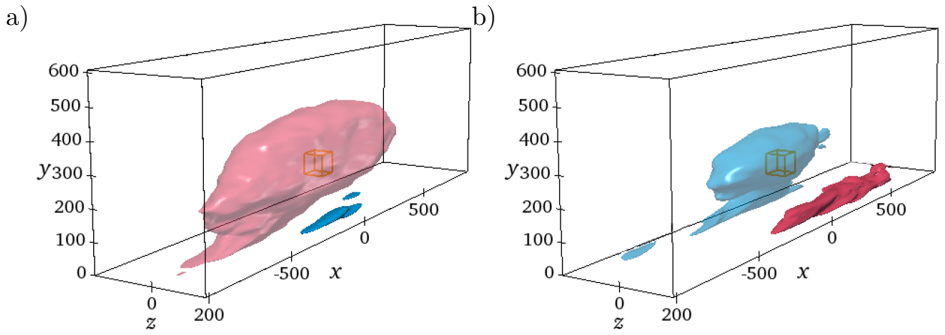

Figure 1: Iso-surfaces of conditional streamwise fluctuation velocity around (a) significant and (b) irrelevant perturbation cells, low-pass filtered at $\Delta = l_{cell}$. Red: u^+=0.6; blue: $u^+ = -0.03$. A small cube indicates the position and size of perturbation cell. $y^+_{cell} = 150$, $l^+_{cell} = 75$.

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[1]Jiménez, *Europ. J. Mech. B: Fluids* **79**, 1 (2019).
[2]Encinar and Jiménez, arXiv:2302.04630 (2023).
[3]Lozano-Durán, Flores and Jiménez, *J. Fluid Mech.* **694**, 100-130 (2012).