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# Time-resolved Evolution of the Wall-bounded Vorticity Cascade

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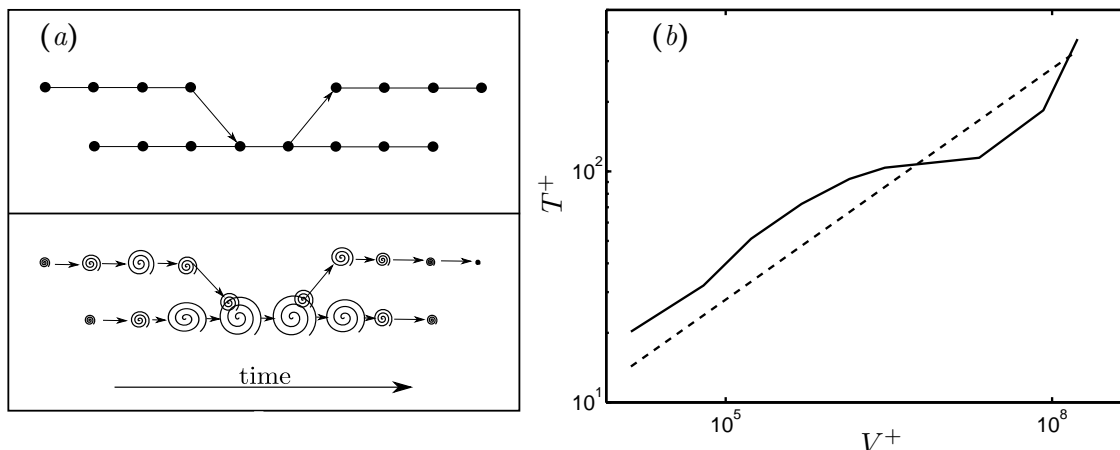
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**Abstract.** The temporal evolution of vortex clusters in a turbulent channel at  $Re_\tau = 950$  is studied using DNS sequences with temporal separations among fields short enough for individual structures to be tracked. From the geometric intersection of structures in consecutive fields, we build temporal connection graphs of all the vortex clusters, and, from their properties, define main and secondary branches for each evolution. It is found that the average lifetime of the clusters within a branch is proportional to the cube root of their maximum volumes, and that they move approximately with the local mean velocity. Especial attention is paid to their wall-normal displacement. It is found that their probability of moving away from the wall is only slightly higher than that of moving towards it, and that this behaviour is independent of the wall distance at which the branch is initially created. Finally, direct and inverse physical cascades are defined, associated with the splits and mergers between structures. It is found that the direct cascade predominates, but that both directions are roughly comparable.

## 1. Introduction

The efforts to describe wall-bounded turbulent flows in terms of coherent motions date at least to the experiments in Kim *et al.* (1971). Those structures have played an important role in the understanding of turbulence organization and its dynamics. Data from individual snapshots of direct numerical simulations (DNS) allow us to study the three-dimensional statistical properties of those objects, but their dynamics can only be fully understood by tracking them in time. Although the temporal evolution has already been studied for small structures at moderate Reynolds numbers (e.g., Robinson, 1991), a temporal analysis of three-dimensional structures spanning from the smallest to the largest scales across the logarithmic layer has yet to be performed.

Different models involving coherent structures have been proposed to represent the organization of wall-bounded turbulent flows. Using PIV measurements, Adrian *et al.* (2000) conceived a model built on packets of hairpins that grow from the wall, in which the hairpins work cooperatively to generate low-momentum ramps. A different view was presented by del Álamo *et al.* (2006), who extracted coherent vortical structures from DNSes and proposed a less organized scenario. Although the two models are fairly similar kinematically, they have important dynamical differences, mostly regarding the relevance of the interactions with the wall. Another open question is whether the cascade proposed by Kolmogorov (1941), is not only a conceptual way of organizing the flow, but an actual physical process undergone by the



**Figure 1.** (a) Upper part; sketch of a graph with three branches, one merger and one split. Bottom part; sketch of the vortex clusters which are represented in the previous graph. (b) (—), average lifetime of the evolutions,  $T$ , as a function of the maximum volume,  $V$ , attained by the branch, (---),  $T \propto V^{1/3}$ .

coherent structures. The most interesting problems lie in the logarithmic region, which is the seat of cascades of vorticity, energy, and momentum. To answer those questions, we develop in the present paper a method to track coherent structures in time, and use it to characterize the temporal evolutions of vortex clusters in a turbulent channel where both the Reynolds number is high enough to include a non-trivial range of length scales, and the domain is sufficiently long and wide to contain at least some of the largest structures.

The numerical experiments and the method employed to track the clusters are described in section 2. The statistical properties of the evolutions are presented in section 3, and conclusions are offered in section 4.

## 2. Numerical experiments and tracking method

The data are obtained from a DNS of a turbulent channel at  $Re_\tau = 950$  over 10 eddy turnovers, long enough compared with the lifetimes of the coherent structures not to interfere with their description. Snapshots are stored every  $\Delta t^+ \simeq 1.1$ , to ensure that the structures can be properly tracked in time, resulting in around  $10^4$  flow fields. The + superscript denotes wall units, defined in terms of the friction velocity and of the kinematic viscosity. To make the problem tractable, the streamwise and spanwise dimensions of the channel are kept small,  $L_x/h = \pi$ ,  $L_z/h = \pi/2$ , where  $h$  is the channel half-width. Flores & Jiménez (2010) showed that this box is large enough to capture the physics of the logarithmic layer. The structures tracked are the vortex clusters defined by del Álamo *et al.* (2006) in terms of the discriminant of the velocity gradient. They are self-similar objects in their three characteristic lengths, with sizes that span from the Kolmogorov scale,  $\eta$ , to the channel half-width, so that structures in the logarithmic layer are included. Geometrically, they are 'sponges of strings' with a thickness of the order of  $7\eta$ , but without a clearly defined shape (Jiménez, 2012). The average velocity field conditioned to the presence of a vortex cluster is an ejection flanked by a pair of counter-rotating vortices, and a low-velocity streak spreading downstream.

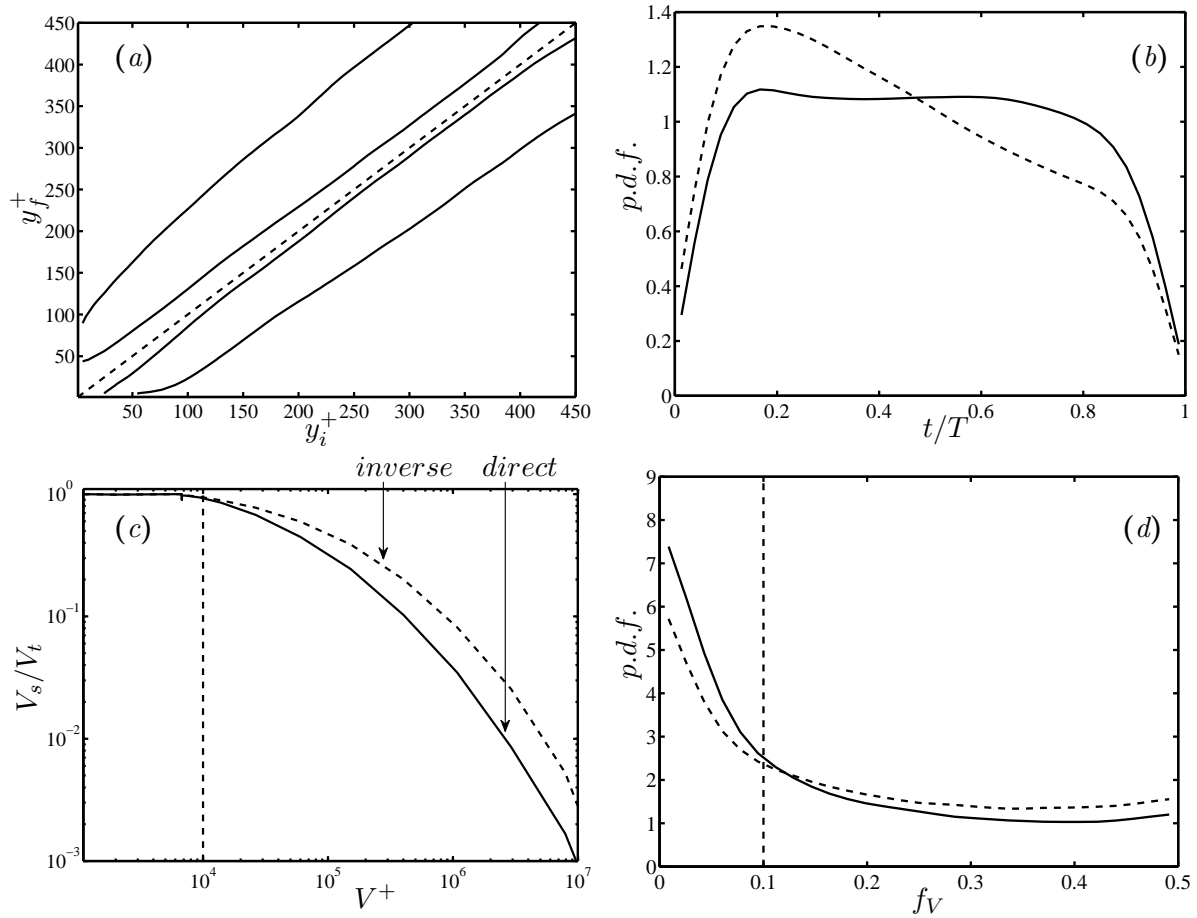
Vortex clusters are tracked in time by looking at the volume of the intersections between structures in consecutive flow fields. Those temporal connections are used to build a graph in which each snapshot of a cluster is a node, and their connections are edges. A cluster is

considered to evolve without merging or splitting when it has exactly one backward and one forward connection. Clusters with more than one backward connection are considered to have formed by merging of previously-existing ones, and those with several forward connections are said to split. Mergers and splits are interpreted as cascade processes, suggesting that it is better to organize the flow history into coherent branches than to deal with the full evolution graph. As a consequence, branches are the units of our study. A graph with three branches, one merger and one split, is sketched in figure 1(a). The criteria used to organize the graph in branches are based on the parameter  $w = \Delta V/V_i$ , where  $\Delta V$  is the volume difference between two connecting clusters and  $V_i$  is the volume of their intersection. Note that  $w$  is not associated with the nodes of the graph, but with the edges. When a node is backward-connected with more than one node, or when two or more nodes are backward-connected with the same node, the algorithm continues the branch with the lowest  $w$ . The rest of the branches involved in the process are considered to either end or be newly created at that instant, depending on the case. The physical interpretation of those criteria is that the algorithm tries to continue the branch containing the largest cluster.

### 3. Results

Since the properties of the vortex clusters are known for all times, once the tracking process has been done we can focus on any one of their features, and study the statistics of its temporal evolution. As it could be expected, the average lifetime,  $T$ , of a branch increases with its maximum volume,  $V$ , i.e. the volume of the biggest vortex cluster that belongs to the branch. Figure 1(b) shows that  $T \propto V^{1/3}$ , where  $V^{1/3}$  can be interpreted as a characteristic length scale of the structure. Circumscribing each vortex cluster within a box, and looking at the evolution of its centre, we can estimate the velocity at which the clusters move in the channel. The results show that the centres of the clusters are basically advected with the local mean profile in the streamwise direction, whereas the spanwise and wall-normal velocities are of the order of the friction velocity. We also study the tendency of the centres of the vortex clusters to move towards or away from the wall by looking at their initial and final wall distances. Figure 2(a) shows that the clusters in each branch move up or down by at most  $\sim 100$  wall units during their lifetime, with a slightly higher probability of moving away from the wall. That behaviour is independent of the wall distance at which the cluster is initially created. In particular, there is little evidence that most branches originate near the wall and move into the outer layers.

One of the most interesting things that can be sought is whether or not there is a cascade, not only as a way to conceptualise the flow, but as an actual physical process in which coherent structures merge and split. The volume of a branch can change either smoothly, when the clusters are not merging or splitting, or through sudden changes. The processes of merging and splitting can be thought as a direct (when splitting) or an inverse (when merging) cascade. Figure 2(b) shows the fraction of smooth growth and decay as a function of the maximum volume attained by a branch, and it can be observed that there is a minimum volume  $\sim (15\eta)^3$  above which mergers and splits begin to be important. Although the curves for the direct and the inverse cascades are not identical, it is intriguing how similar they are, recalling the ‘backscatter’ observations of Piomelli *et al.* (1991) and others. Figure 2(c) shows the probability density functions (p.d.f.s) of the times when mergers or splits take place during the life of a branch, and reveals that splits have a flat distribution, while mergers are more probable at the beginning of the life. In order to study those processes in more detail, figure 2(d) shows the p.d.f.s of the fraction of volume gained or lost when merging or splitting. Two different regions can be identified: the first one represents fractions of volume that are of the order of the characteristic size of the cluster involved, and follows a uniform distribution with very little differences between merging and splitting. We can call this region ‘inertial’. The second region represents volume fractions



**Figure 2.** (a) P.d.f. of the wall-normal distance of the clusters at the end of the evolutions,  $y_f$ , as a function of the wall-normal distance at their initial creation,  $y_i$ . Contours are 50% and 98% of the data. The dashed line is  $y_f = y_i$ . (b) P.d.f. of when mergers (---) and splits (—) take place during the life of a branch,  $t$ , normalized with its lifetime  $T$ . (c) Fraction of smooth growth (---) and decay (—) as a function of the maximum volume attained by the branch,  $V$ .  $V_s$  and  $V_t$  are the smooth and total change of volume. The vertical dashed line is  $V \simeq (15\eta)^3$ . The value  $1 - V_s/V_t$  represents the fraction of direct or inverse cascade. (d) P.d.f. of the fraction of volume,  $f_V$ , gained (---) or lost (—) when merging or splitting. The vertical dashed line is  $f_V = 0.1$ .

that are small compared with the volume of the cluster, and, for them, there are slightly more splits than mergers. Those pieces are of the order of the (Kolmogorov) thickness of the cluster and they can be called 'viscous'. They are the only clearly irreversible aspect that can we have been able to isolate from the branch histories.

#### 4. Conclusions

We have characterized the temporal evolutions of vortex clusters in a turbulent channel with  $Re_\tau = 950$ , using data from a DNS with temporal separations among fields short enough for individual structures to be tracked. We have developed a method to track the vortex clusters in time, based on the geometric intersection of structures in consecutive fields, and we have

built temporal connection graphs, and classified them into interconnected branches. Although this method is applied here to track vortex clusters, it can be employed with any other type of coherent structures.

By analysing the features of the branches, it is found that their lifetimes are proportional to the cube root of the maximum volume attained by them, and that they are basically advected by the local mean profile in the streamwise direction. Looking at the wall-normal displacement of the clusters, it is found that their probability of moving away from the wall is only slightly higher than that of moving towards it, and that this behaviour is independent of the wall distance at their inception. This suggests that the wall plays a relatively minor role in the dynamics of these coherent motions. Finally, physical direct and inverse cascades are defined by looking at the splits and mergers between structures. The process of merging is interpreted as an inverse cascade, whereas splitting can be interpreted as a direct one. It is found that vortex clusters whose characteristic lengths are above approximately  $15\eta$  undergo simultaneous direct and an inverse cascades, but merging tends to be more common towards the beginning of the evolution of each branch. Even if the direct cascade predominates over the inverse one, it is surprising how similar both cascades are.

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