TIME-RESOLVED EVOLUTION OF WALL-BOUNDED DIRECT AND INVERSE CASCADES IN TURBULENT CHANNELS AT Re$_\tau = 4000$

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Abstract The temporal evolution of the structures responsible for the momentum transfer in a turbulent channel at $Re_\tau = 4000$ is studied using DNS sequences with temporal separations among fields short enough for individual objects to be tracked. Direct and inverse physical cascades are associated with the process of structures splitting and merging respectively. It is found that the direct cascade predominates, but both directions are roughly comparable. Most of the merged and split fragments have small sizes of the order of some Kolmogorov units. However, an inertial self-similar process is found in which the structures merge and split in fragments of comparable sizes. Finally, a link is established between places with high Reynolds stresses and the predominance of either the direct or the inverse cascade.

NUMERICAL EXPERIMENTS AND TRACKING METHOD

The data are obtained from a direct numerical simulation of a turbulent channel at $Re_\tau = 4000$[1] over 10 eddy turnovers, long enough compared to the lifetimes of the coherent structures that there is no interference with their description. Snapshots are stored every $\Delta t^+ \simeq 2$, to ensure that the structures can be tracked, resulting in around 10^4 flow fields. To make the analysis feasible, the streamwise and spanwise dimensions of the domain are kept moderate, $L_x/h = 2\pi$, $L_z/h = \pi$, where h is the channel half-width, but nevertheless large enough to capture the physics of the logarithmic layer [1]. The structures tracked are defined as places where the tangential Reynolds stresses, $-uv$, are high (details in [2]). They are self-similar objects in their three characteristic dimensions, and span sizes from a few Kolmogorov scales to the full channel height. They, therefore, include log-layer structures. Geometrically, they are irregular flakes with a thickness of the order of 15 Kolmogorov units (η). The structures are tracked in time by looking at the volume of the intersections between structures in consecutive flow fields. The temporal connections are used to build a graph in which the objects are represented by nodes and their connections by edges. A structure evolves without merging or splitting when it has exactly one backward and one forward connection. Objects with more than one backward connection are considered to have formed by merging of several previous ones and those with several forward connections are said to split. Finally, mergers and splits are considered physical representations of the turbulent cascade. A graph with two branches and one split is sketched in figure 1(*a*). We define the characteristic size of a structure as the diagonal of its circumscribed three-dimensional box and the characteristic size of a branch as the maximum of all the structures it is made of. When talking about merging or splitting, we denote the size of the largest and the smallest structures involved in the process as l_b and l_s respectively.

RESULTS

Figure 1(*b*) shows the fraction of the number of branches that undergo a direct or an inverse cascade, i.e., that split or merge respectively at least once in their lives, as a function of the characteristic size of the branch. It can be observed that there is a size of ~ 100 wall units above which mergers and splits begin to appear. Below this value, the graphs are made of only one branch that evolves without splitting or merging. On the other hand, when the characteristic size is greater than ~ 600 wall units, all the branches merge and split at least once in their lives. In between these two values, the direct cascade always dominates and there are branches that split but never merge. Although the curves for the direct and the inverse cascades are not identical, it is intriguing how similar they look, recalling the backscatter observations of [3] and others. To study in more detail the problem, figure 2(*a*) shows the probability density functions (p.d.f.s.) of the sizes of the fragments merged or split. Most of the them are of the order of 20η, and correspond to a viscous process. However, the tails of the p.d.f.s reveal that the structures also split and merge by fragments of comparable sizes. The spatial organization of mergers and splits is studied by looking at the relative position of the centers of the smallest fragment with respect to largest ones and the results (not shown) reveal that most of the them take place in the streamwise direction. The structures merge with objects in front of them and lose structures from behind. This is consistent with the observation of large coherent structures elongated in the streamwise direction that could be formed by joining several fragments in such direction. In addition, other asymmetries between the direct and inverse cascades are found. Splits tend to happen more often at the end of the life of the structures and they are presumably responsible for their disappearance, whereas the mergers are more probable at the beginning. Finally, the subgrid-scale dissipation $\varepsilon_{sgs} = \tau_{ij}\widetilde{S_{ij}}$, with τ_{ij} the subgrid-scale stress tensor and $\widetilde{S_{ij}}$ the filtered rate-of-strain tensor, is computed using the structures themselves to perform

[1]The results presented in this abstract were obtained for a turbulent channel at $Re_\tau = 2000$, although the data for $Re_\tau = 4000$ will be shown in the final version of the work.

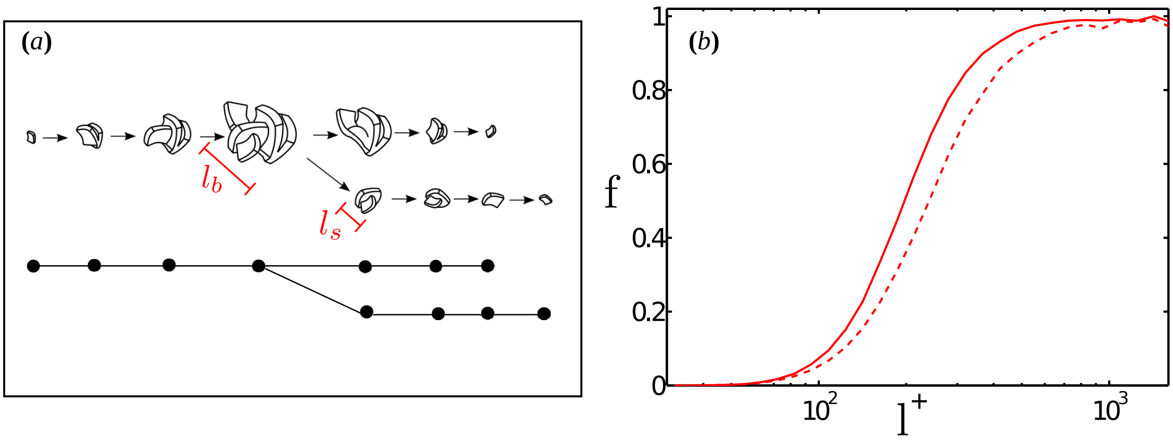

Figure 1. (*a*) Upper part; sketch of the temporal evolution of a coherent structure. Bottom part; graph representation of the temporal evolution. (*b*) Fraction, f, of the number of branches that undergo a direct (——) and an inverse (– – –) cascade as a function of the characteristic size of the branch, l, in wall units.

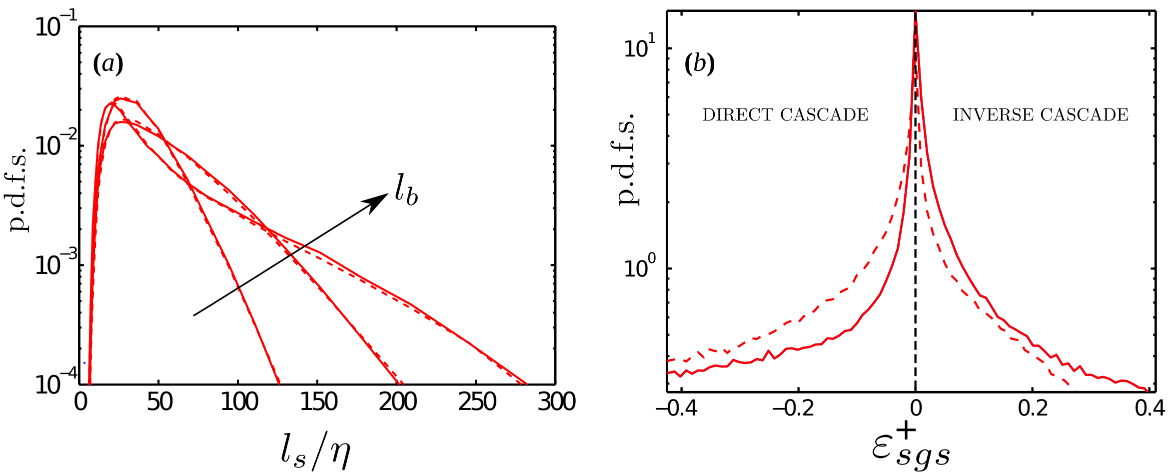

Figure 2. (*a*) Probability density functions of the sizes of the structures merged or split, l_s, normalized in Kolmogorov units and for different characteristic sizes of the largest structure involved, $l_b^+ = 0-100, 100-200, 200-600$. ——, inverse cascade (mergers); – – –, direct cascade (splits). (*b*) Probability density functions of the subgrid-scale dissipation, ε_{sgs}. ——, actual coherent structures (skewness 0.5); – – –, randomly re-distributed coherent structures (skewness -0.9).

the filtering, so that, $\widetilde{(*)} = 1/V \int_V (*) \mathrm{d}V$, where V is the volume of the structure. Note that, by definition, the structures are located at places where $-uv$ is high. Figure 2(*b*) shows that the p.d.f. of ε_{sgs} is slightly skewed towards the inverse cascade (skewness 0.5). In order to test the effect of intense $-uv$ within the objects, the structures were re-distributed randomly in the domain, moving their wall-parallel position but keeping their wall-normal location and shape. Moreover, this was done without changing the underlying flow field, so that the new structures do not necessarily have intense $-uv$ anymore. When re-computing ε_{sgs}, the p.d.f. become more skewed towards the direct cascade (skewness -0.9), suggesting that the predominance of either the direct or the inverse cascade is related to the presence of strong Reynolds stresses.

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