BYPASS TRANSITION IN BOUNDARY LAYERS AS AN ACTIVATED PROCESS

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Abstract We consider the spatio-temporal aspects of the transition to turbulence in a boundary layer above a flat plate exposed to free-stream turbulence. Combining results from the receptivity to free-stream turbulence with the observation of a double threshold from transition studies in e.g. pipe flow we arrive at a physically motivated prediction for the spatial distribution of nucleation events in boundary layers. We use a cellular automaton to implement a complete model for the spatial and temporal evolution of turbulent patches and show that the model reproduces the statistical features of the boundary layer remarkably well. The success of the modeling shows that bypass transition occurs as a spatiotemporally activated process, where transition is triggered by critical fluctuations imported from the free-stream turbulence.

SETTING

We present a probabilistic cellular automaton model to describe the spatio-temporal aspects of bypass transition in boundary layers. With this we extend recent results on parallel shear flows to spatially developing external flows. The spatial behaviour of shear flows close to transition has successfully been related to probabilistic cellular automata and directed percolation [1, 2, 3]. The most notable results stem from pipe flow, where at low Reynolds number turbulence exists in the form of localized puffs, which may decay or split with probabilities depending on Re. We extend the concept to turbulence transition in a flat-plate boundary layer subject to free-stream turbulence. If the amplitude of the free-stream disturbances exceeds a threshold, the traditional route via Tollmien-Schlichting waves can be bypassed and transition happens without exponential amplification of linear instabilities. In this context, turbulent spots are created, which spread while travelling downstream. The intermittency factor, measuring the fraction of turbulent sites, grows from zero at the inflow to one for full turbulence in an S-shaped curve.

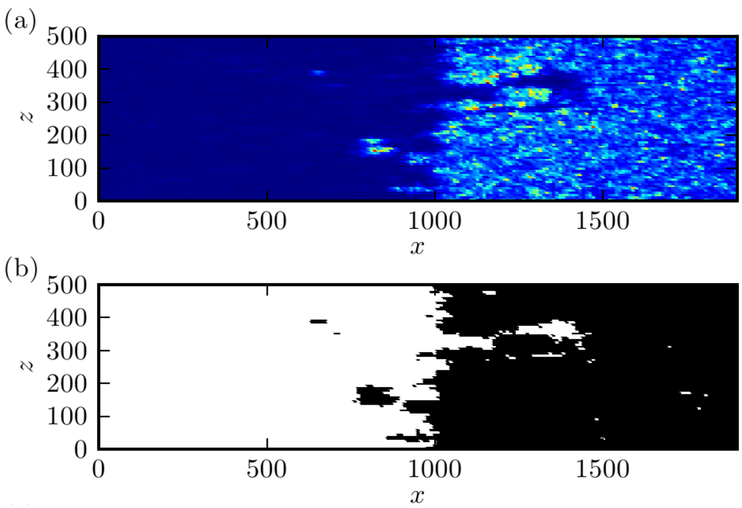

Figure 1. Visualization of turbulent spots in the LES data. (a) The untreated LES data. The colors indicate the level of turbulence by measuring the spanwisel shear stress at the wall. Dark blue indicates low intensities, the bright regions higher intensities. (b) Digitized LES data where only laminar (white) and turbulent (black) regions are distinguished. These data are then used to extract the parameters for the cellular automaton model.

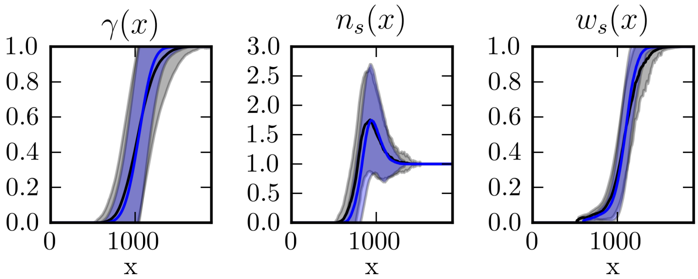

Figure 2. Comparison of statistics between the LES data (black) and the probabilistic cellular automaton (blue). (a) Intermittency factor. (b) Number of spots at every downstream position. (c) Width of independent spots in units of the domain width as a function of downstream position. The shaded areas indicate one standard deviation and show that not only the mean of the qantities agrees very well but also the second moment of the distribution.

SPOT NUCLEATION AND EVOLUTION

Combining results from the receptivity of a laminar boundary layer to free stream turbulence with the observation of a double threshold in Reynolds number and perturbation amplitude in internal shear flows [4], we develop a predictive model for position dependent spot nucleation rates. The model is completed by a probabilistic cellular automaton (PCA) describing the evolution of turbulent spots in the boundary layer flow.

The model parameters are obtained directly from statistical analysis of data from large LES at various turbulence intensities with a setup similar to ref. [5], see figure 1. The nucleation model together with the PCA reproduces the statistics of the LES data extremely well (figure 2), showing that the spatial evolution of turbulent spots in a transitional boundary layer is described by our model.

References

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