Sustainability and Dynamics of Transport Barriers Near the Density Limit

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Abstract / Objectives

Abstract Numerous studies have demonstrated that edge shear layers generated by drift waves collapse when the adiabaticity parameter $\alpha = k_{\parallel}^2 V_{\rm th}^2/\omega_{ci}\eta$ is decreased below $\alpha_{\rm crit} \sim 1$. We have investigated the role of this parameter and the initial density contrast in the formation and dynamics of transport barriers, using the Hasegawa-Wakatani (HW) model. This study is relevant to the fate of shear layer and transport barriers near the density limit.

We also apply the HW model to a density profile formed after, e.g., a pellet- or supersonic neutral beam injection, or other means of build-up. In this setting, no shear flow is initially imposed but rather created by the drift waves generated by the density gradient itself. The density profile then relaxes under the competition between the turbulent transport and its suppression by the shear flow. The relaxation dynamics generically go through a staircase phase, wherein the initial density step splits into smoother steps separated by flat density regions. This process is accompanied by the shear flow formation and suppression of the turbulent transport. The final breadth of the transport barrier depends on the adiabaticity α and the initial density contrast, Δn. Turbulent fronts propagate at approximately the same radial speed in both directions away from the initial localization of the transport barrier, again, depending on the density contrast Δn and adiabaticity α.

Overview The HW model offers a vital link between the experiments or full-scale 3D simulations and reduced 1- or 0-D physical models. The reduced models often provide a crucial insight into transport bifurcations. We have narrowly tailored the HW model to this end. Apart from the traditional doubly-periodic box setting, we use a channel setting. It accommodates the density/temperature contrasts across the channel, thus elucidating the net-flux-driven turbulence. After benchmarking and comparing our code with the doubly-periodic HW simulations, investigating the zonal flow (ZF) dependence on the model parameters (e.g. number and strengths of ZF jets in the channel vs the adiabaticity $\alpha = k_{\parallel}^2 V_{\rm th}^2/\omega_{ci}\eta$ and instability driver κ) we have focused on two objectives:

(1) Collapse of edge shear layers on a high-density side of the channel, where the adiabaticity α, that acts as a flow bifurcation parameter, drops below $\alpha_{\rm crit} \approx 1$. $\nabla\alpha$ triggers the formation of a barrier shear layer, which separates the region of isotropic turbulence from ZF-dominated. The barrier is pinned to the location of $\alpha_{\rm crit}$ and does not propagate. We observe that this spontaneously generated shear layer forms where $\alpha = \alpha_{\rm crit}(\kappa)$ and disappears where $\alpha < \alpha_{\rm cr}$ inside of the domain (κ is the DW driver). This behavior is consistent with that observed at the density limit when high edge density forces a drop in the edge layer value of α.

(2) Decay and relaxation of a step-like density profile formed after, e.g., a pellet- or supersonic neutral beam injection or other means of build-up. In this simulation set-up, no shear flow is initially imposed but created by the ∇n -driven DWs. Both internal- and edge barriers are formed if $\alpha \sim 1$ and $\Delta n \gg n_{\rm min}$, where $n_{\rm min}$ is the density at the lower-density side of the channel. We observe a noticeable difference between the flux suppression mechanisms on the high- and low-density sides of the transport barrier.

Modified Hasegawa-Wakatani Model: $\frac{\partial\zeta}{\partial t} + \{\phi,\zeta\} = \alpha\left(\tilde\phi - \tilde n\right) - D\nabla^4\zeta;$ $\frac{\partial n}{\partial t} + \{\phi,n\} = \alpha\left(\tilde\phi - \tilde n\right) - \kappa\frac{\partial\phi}{\partial x} - D\nabla^4 n;$ $\zeta \equiv \Delta\phi;$ $\alpha = k_{\parallel}^2 V_{\rm Te}^2/\eta\omega_{\rm ci}$

Here $\{f,g\} \equiv (\partial_x f)\,\partial_y g - (\partial_x g)\,\partial_y f$, $\kappa = n_0^{-1}\partial n_0/\partial y$, where $n_0(y)$ is an equilibrium density profile, and n is a deviation from it, normalized to $n_0(0)$.

Units

$$x/\rho_{\rm s} \to x, \quad \omega_{\rm ci} t \to t, \quad e\phi/T_{\rm e} \to \phi, \quad n_1/n_0 \to n$$

where $\rho_{\rm s} = C_{\rm s}/\omega_{\rm ci}$, $C_{\rm s} = T_{\rm e}/M$, $n = n_0(y) + n_1$.

Simulation

In most HW doubly-periodic simulations α and κ are constant. As $\kappa \equiv n_0^{-1} dn_0/dy$, $n_0(y)$ is exponential, thus changing by $\exp(\kappa L)$ between the boundaries, which becomes unrealistically high for typical parameters. In a channel setting, we may vary $\kappa(y)$. For example, we use a linear rather than exponential profile of $n_0(y)$, which is more appropriate for the middle part of the pedestal.

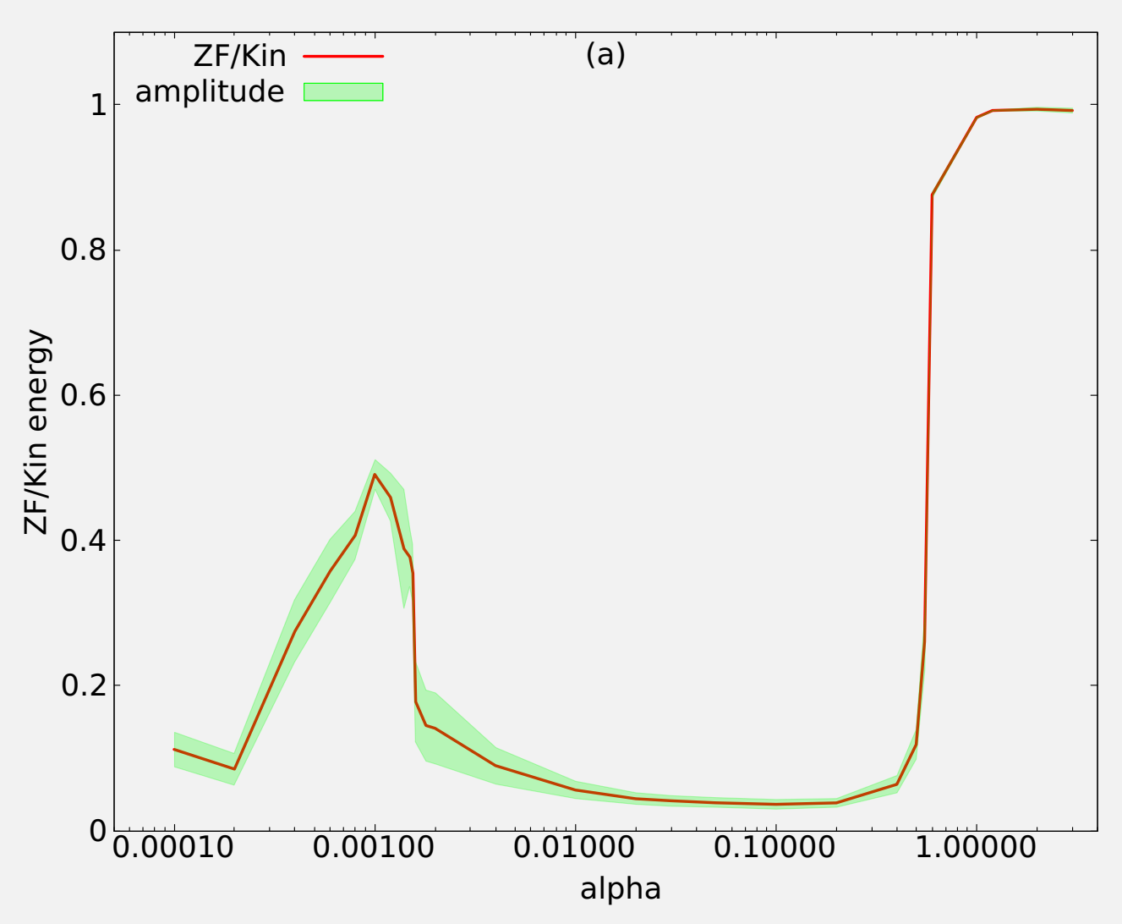
Simulation Results: α -dependence of ZF efficiency — decay of a density step — turbulence spreading — flux suppression by ZF and vortices

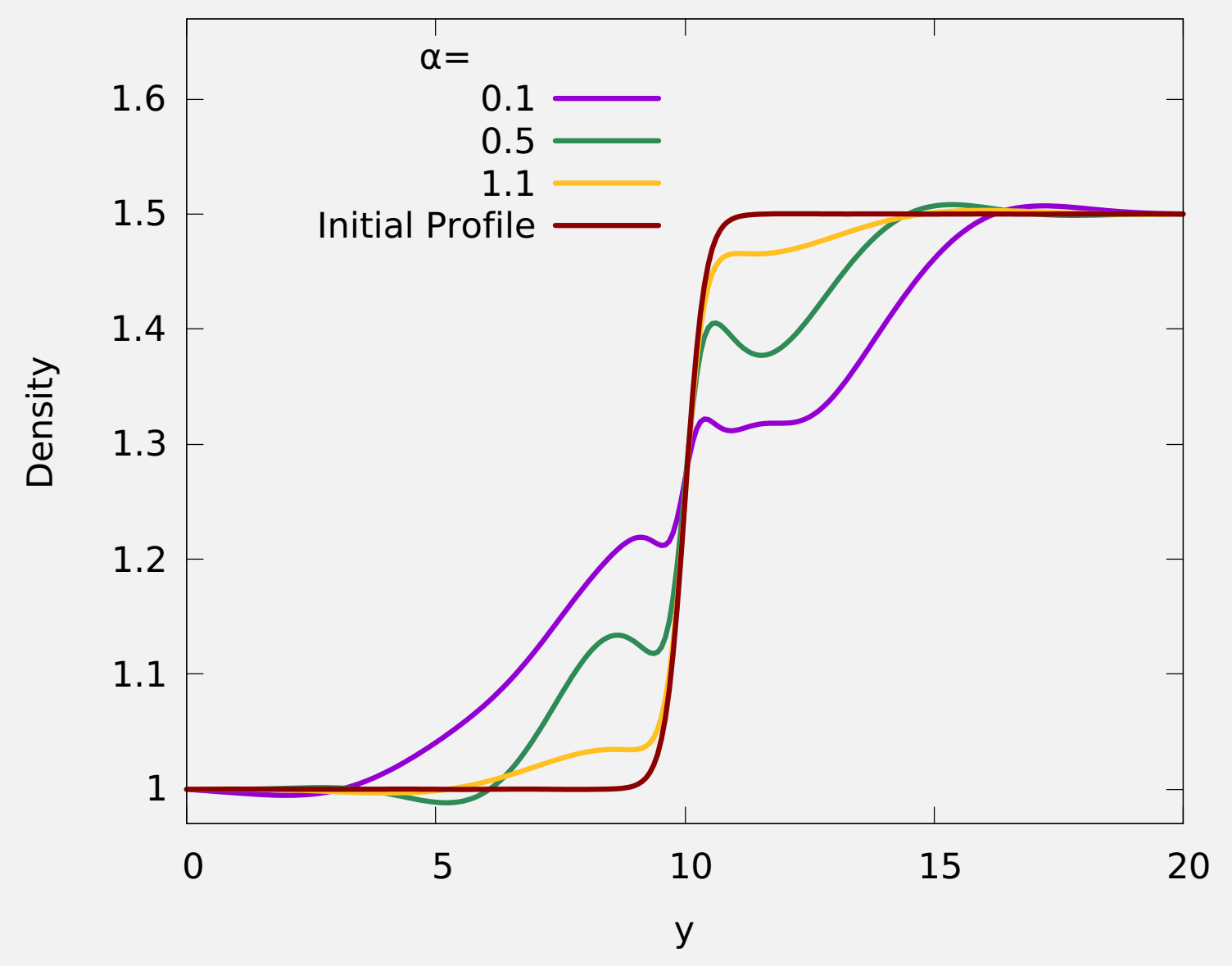
ZFefficiency: $\epsilon = E_{ZF}/E_k \equiv \int(\partial\phi/\partial y)^2 dxdy \Big/ \int|\nabla\phi|^2 dxdy$

— ϵ vs α for the channel flows for $\kappa = 0.3$ and relaxation of the initial density step for different α

— **NB**: back transition from a 50% ZF state at $\alpha \ll 1$

— density gradient inversion due to strong vortices (see a stream function example)

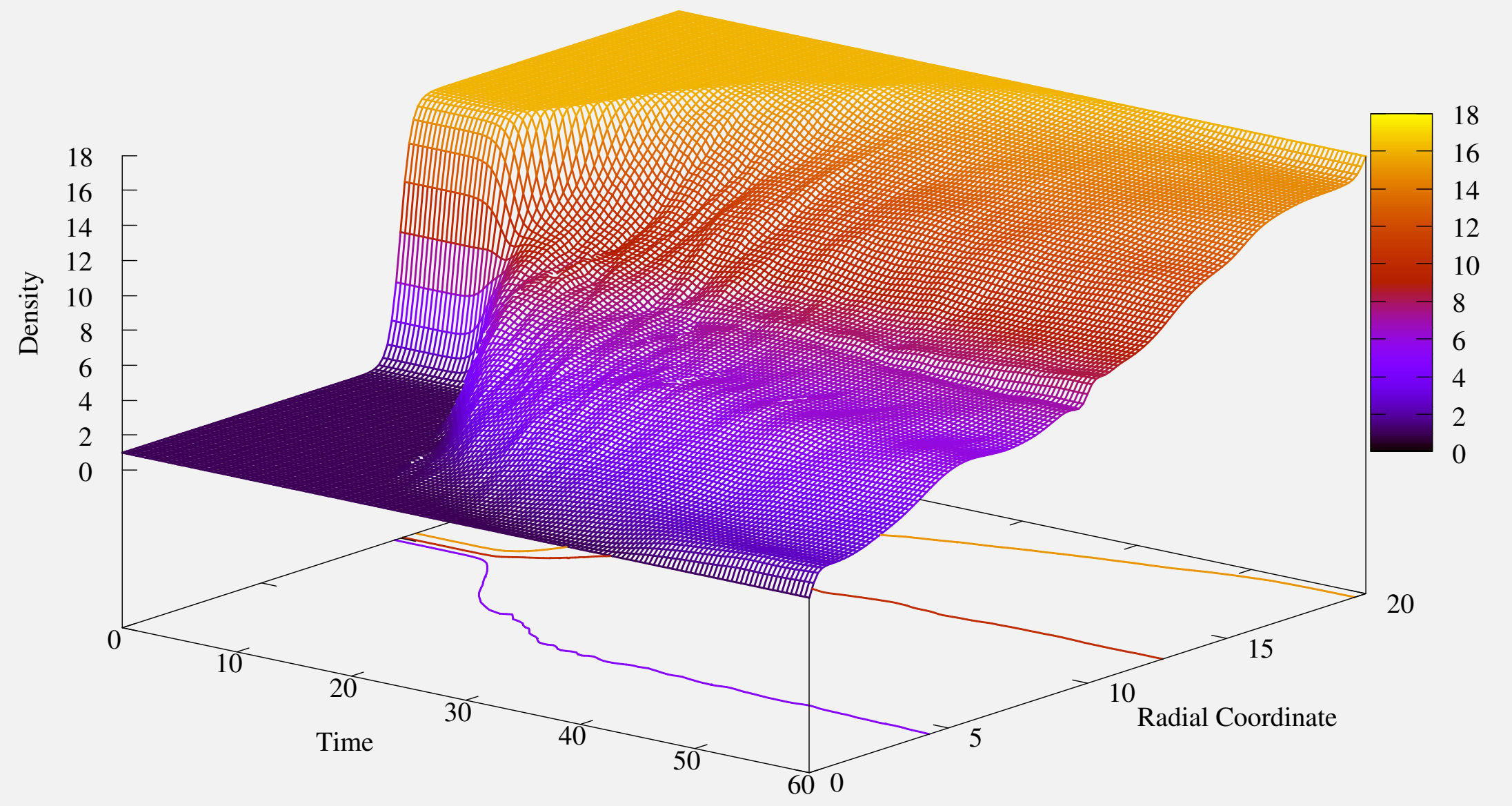


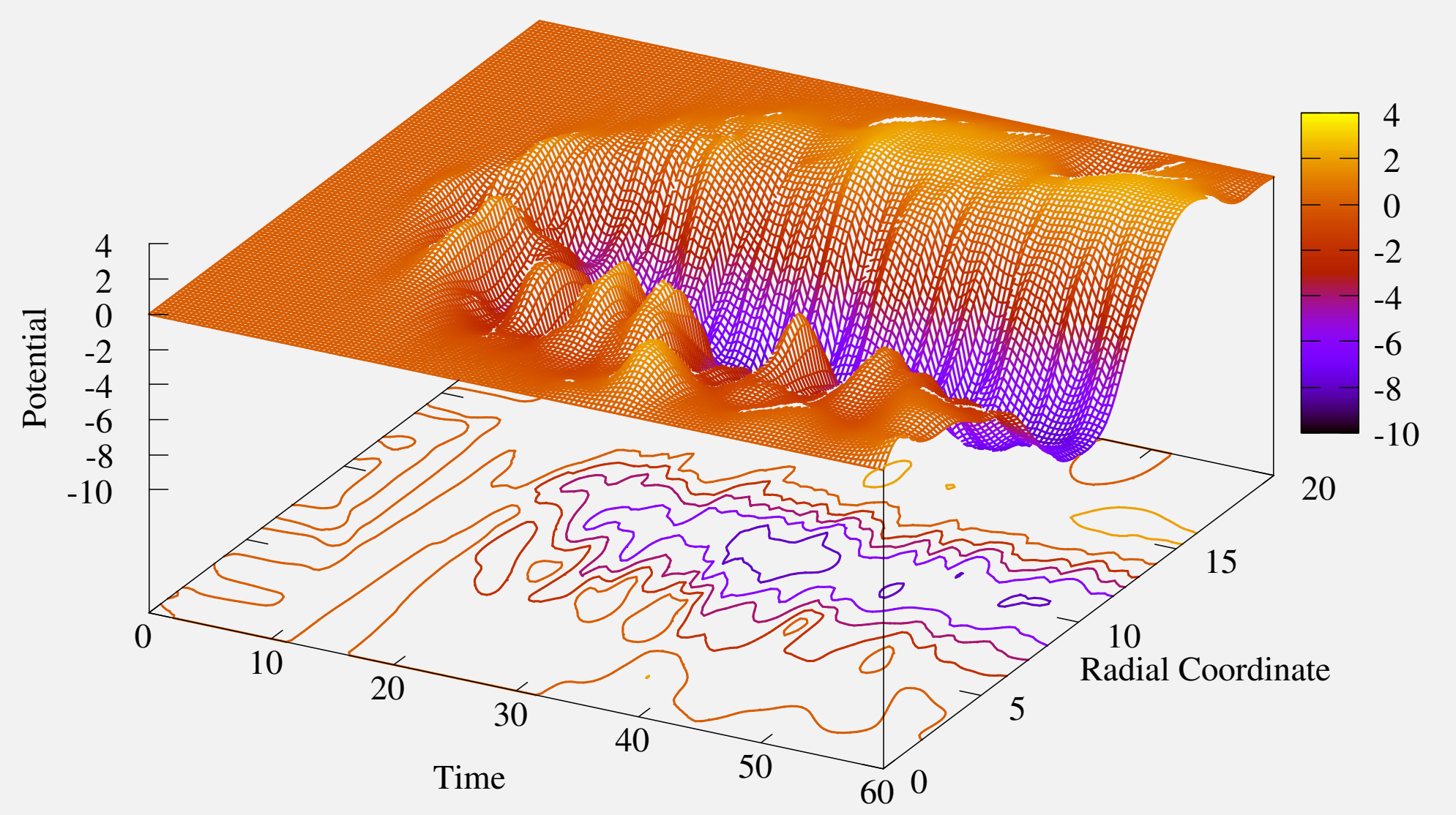


Zonal-averaged density evolution starting from a step profile.

NB: Internal and edge barrier in the final state

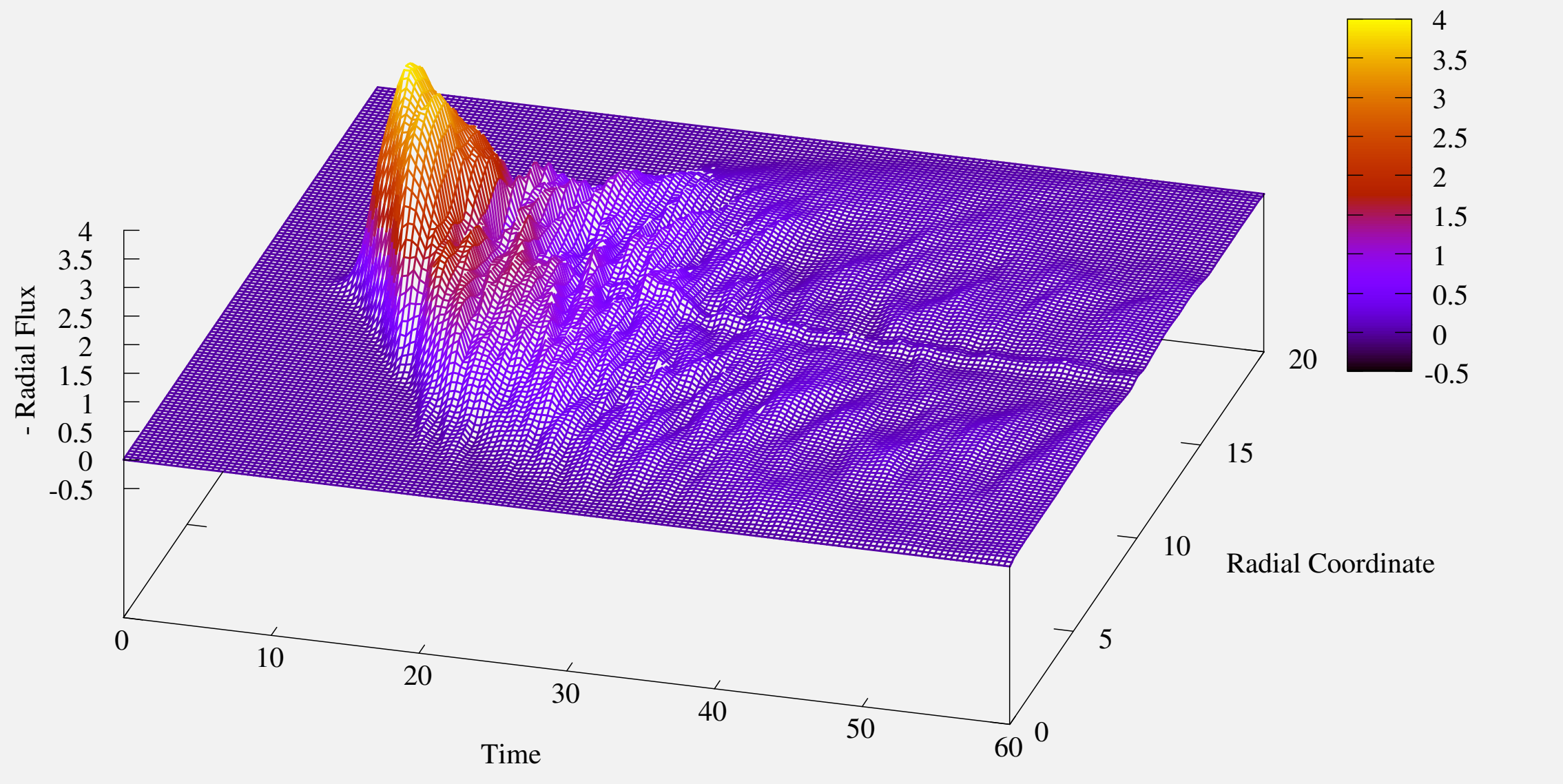
— staircase-like structure





Stream function, showing strong vortices formed in the foot region of the density landscape and two opposite jets adjacent to the initial density cliff, were the growth rate was at maximum.

Turbulent flux, strogly suppressed after the ZFs and vortices are generated.



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Wednesday, October 19, 2022 Room: Exhibit Hall A and Online 2:00-3:30pm, 3:45-5:00