# Spatio-temporal dynamics of turbulence coupling with zonal flows

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In order to predict or control of spatial profiles of plasmas, such as density and temperature, the understanding of how the turbulence is distributed spatially is essentially important. Interaction of turbulence with meso/macro scale shear flows has significant impact on the profile of the turbulence [1]. Moreover, there are several mechanisms that turbulence propagates spatially, such as turbulence spreading [2], and avalanche [3]. The spatial profile of the turbulence is determined by the interaction of the sheared flows and the propagation of the turbulence.

In this study, the role of the phase space dynamics of the turbulence on the spatial distribution and the propagation of the turbulence is investigated. Here, the phase space consists of the wavenumber-space and the real-space. The trapping of the turbulence by the sheared flow appears as the phase space dynamics [4, 5]. Geodesic acoustic modes (GAMs), which is an oscillatory branch of zonal flows, are chosen as the typical example of the sheared flow, where the experimental observation is relatively easy e.g. [6]. Based on the wave-kinetic theory, we consider the turbulence dynamics for the limiting cases of the GAMs driven by turbulence [7], and by energetic particles (EPs) [8], where EP driven GAMs is called EGAMs. The diagram for the driving

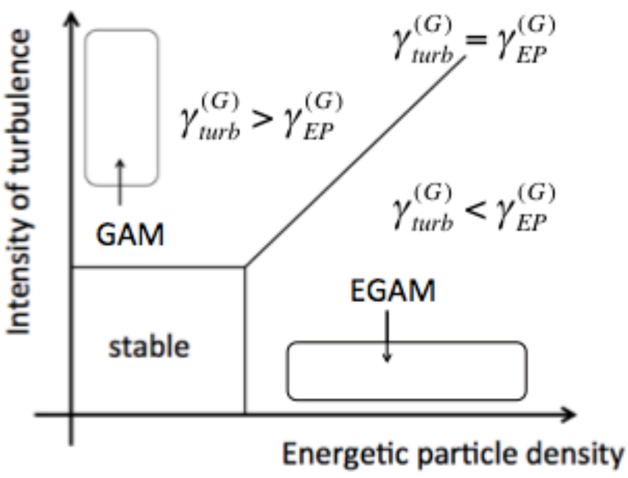


Fig. 1. Diagram for driving forces for GAMs. The growth rates of GAMs due to turbulence and EPs are denoted by $\gamma_{turb}^{(G)}$ and $\gamma_{EP}^{(G)}$, respectively. Here, we consider two limiting cases for $\gamma_{turb}^{(G)} >> \gamma_{EP}^{(G)}$ and $\gamma_{turb}^{(G)} << \gamma_{EP}^{(G)}$.

force of the GAMs is shown in Fig. 1. The limiting cases we consider in this paper correspond to the regions where $\gamma_{turb}^{(G)} >> \gamma_{EP}^{(G)}$ and $\gamma_{turb}^{(G)} << \gamma_{EP}^{(G)}$ for the case of the turbulence driven GAMs, and the case of the EGAMs. Here, the growth rate of the GAMs due to turbulence and EPs are denoted by $\gamma_{turb}^{(G)}$ and $\gamma_{EP}^{(G)}$, respectively. In the following, the turbulence dynamics is shown in each case of the GAM.

The phase space dynamics of the turbulence coupling with the turbulence driven GAM is described [9]. The reduced fluid model is used as the evolution equation of the GAM, and the coupling equation of the GAMs with the wave-kinetic equation for the turbulence is calculated numerically. By assuming the spatially homogeneous turbulence, the periodic boundary condition is used. The perturbation is introduced to the GAM as the initial condition, and the time evolutions of the turbulence and the GAM are studied. The detailed condition for the simulation is given in [9]. The snapshots of the turbulence action $N_k$ in the phase space at $t=0$ and $t=400$ are shown in Fig. 2, where $x$ corresponds to the radial direction, and $k_x$ is the turbulence radial wavenumber. Thus, the snapshot of the turbulence action is related to the radial profile of the radial wavenumber spectrum of the turbulence. The perturbation initially given to the GAMs evolves to have a finite amplitude and the nonlinear saturation is obtained. At the nonlinear saturated state, shown in Fig. 2, the turbulence is trapped in the GAM, so that the phase relation between the turbulence intensity and the GAM velocity is sustained spatially and temporally. Therefore, the turbulence propagates with the GAM phase velocity radially, not with the turbulence group velocity. In order to clarify how the turbulence trapping affects the spatial profile of the turbulence intensity, the energy transfer between the GAM and turbulence is discussed. The energy evolutions for them consits of the energy transfer term via Reynolds stress, and the turbulence trapping term. We show that the trapping term can be comparable to the energy transfer term, which is discussed in a variety of papers e.g, [1]. If one integrates the energy equation with respect to the space, the predator-prey model between

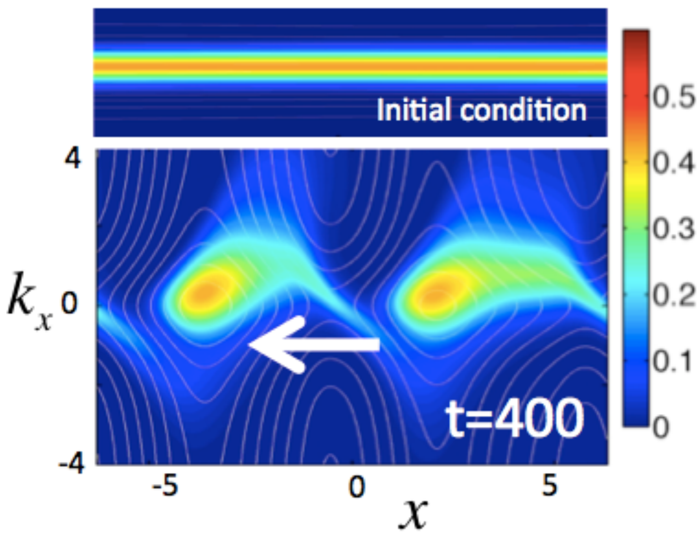

Fig. 2. Snapshots of turbulence action in the phase space. The initial condition $t=0$ , and the nonlinear saturated state $t=400$ are shown.

the turbulence and the GAM can be deduced. The predator-prey model can predict the spatially integrated energies of the trubulencce and the GAM, but is not enough to predict the spatial profile of the turbulence. The turbulence trapping effect is necessary to be considered.

Next, we consider the turbulence dynamics interacting with the EGAM [10]. Spatially inhomogeneous turbulence with the transport barrier interacting in the presence of the EGAM is considered, in order to simulate the situation reported in [11], where the interaction between the turbulence and the EGAM was investigated by a global gyrokinetic simulation. We consider a situation where the turbulence unstable region faces the stable region, and the mean flow shear layer (transport barrier) is localized at the boundary. The turbulence driving force for the EGAM is assumed to be much smaller than that by the EPs, and the energy of the EGAM is treated as a parameter. The EGAM is assumed to propagate from inward to outward the shear layer. The bottom figure in Fig. 3 illustrates the turbulence action in the phase space at a nonlinear saturated state. The turbulence intensity is modulated by the EGAM in the unstable region $x < 20$ . While, the trapped turbulence by the EGAM leaks into the stable region, where there is no turbulence initially. The trapped turbulence propagates with the phase velocity of the EGAM, which is different from the ordinary turbulence spreading [2] and avalanche [3]. By changing the EGAM amplitude, we can evaluated the dependence of the turbulence energy on the EGAM. The turbulence suppression is obtained in the turbulence unstable region, and the turbulence is enhanced by the EGAM at the stable region. Thus, the EGAM has a dual effect on the turbulence transport.

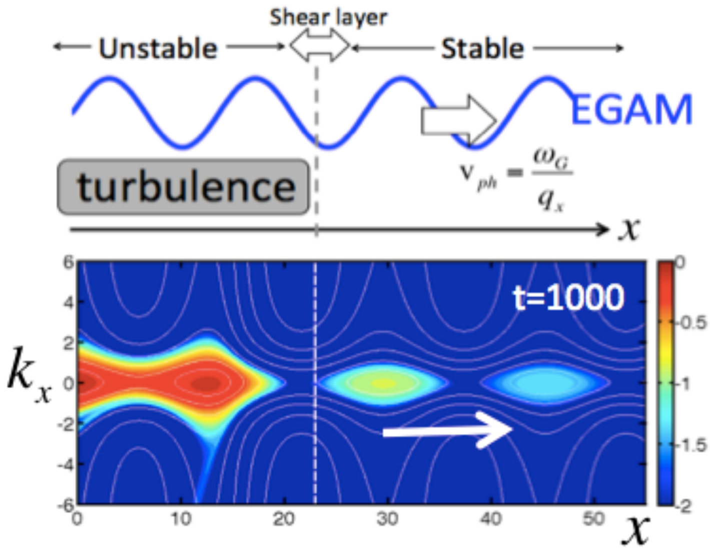


Fig. 3. Model configuration for the turbulence interacting with the EGAM (above). The snapshot of the turbulence action at the nonlinear saturated state (bottom).

For summary, we investigate the dynamics of the drift wave turbulence interacting with GAMs, by focusing on the phase space dynamics, turbulence trapping. In the framework of the wave-kinetic theory, the turbulence coupling with the GAM is considered for the two limiting cases. The case of the GAMs driven by the turbulence is studied, in addition to the case of the EGAMs interacting with the turbulence. The turbulence trapping is shown to be as important as the energy transfer via the Reynolds stress for determining the spatial distribution of the turbulence. It is also discussed that the turbulence trapped by the EGAMs in the turbulence unstable region can penetrate the shear region (transport barrier), and leak into stable region. Thus, the EGAM has a dual effect on the turbulence; the turbulence suppression at the unstable region, and the turbulence enhancement at the stable region. In this way, the turbulence trapping plays important roles for the nonlocal propagation of the turbulence and could be a key mechanism to determine the spatial distribution of the turbulence.

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