Oscillatory behavior of low-frequency fluctuations in gyrokinetic simulations

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One key barrier to realizing fusion power is the turbulent transport in magnetized plasmas. Ion temperature gradients induce micro-instability called ITG mode, and the ITG mode drives plasma turbulence. The turbulence causes the particle/heat transports while exciting zonal flows via nonlinear interactions. The gyrokinetic simulation demonstrated turbulent transport reduction by zonal flows [1]. The flows are expected to be a clue in controlling turbulent transport.

In our work[2], the functional relation was proposed using the time-averaged values of the turbulence component T and zonal flow component Z of electrostatic potential fluctuation, as well as the normalized ion heat diffusivity $\tilde{\chi}_\mathrm{i}$. Based on the relation, we have applied it to time series data of gyrokinetic simulations as,

$$\tilde{\chi}_\mathrm{i}^\mathrm{Model}(t) = \frac{C_1 T(t)^\alpha}{1 + C_2\sqrt{Z(t)}/T(t)}.$$

Here the coefficients (C_1, C_2, α) are the fitting parameters. We have performed gyrokinetic simulations by means of the GKV code[3], which is a local flux tube code. In recent work, it has been found that the functional relation for time series data has more precisely reproduced simulation-generated data than the relation based on time-averaged data[4].

Furthermore, we have artificially introduced time delays of T and Z from $\tilde{\chi}_\mathrm{i}$, respectively represented by Δt_T and Δt_Z, to understand the influence of the correlation between T and Z,

$$\tilde{\chi}_\mathrm{i}^\mathrm{Model}(t, \Delta t_T, \Delta t_Z) = \frac{C_1 T(t-\Delta t_T)^\alpha}{1 + C_2\sqrt{Z(t-\Delta t_Z)}/T(t-\Delta t_T)}.$$

The contour map of the fitting error has indicated that the error is minimized when Z follows T, $\Delta t_T > \Delta t_Z$. On the other hand, the similarity of the contour map has shown that the low-frequency components may dominate the structure of the contour map by using low-pass filtered T, $\sqrt{Z}$, and $\tilde{\chi}_\mathrm{i}$. The low-frequency components have exhibited a high coherence between T and Z. These results imply that the interaction between T and Z of low-frequency imposes a constraint on the time series data, and we should investigate that.

Since zonal flows grow by energy transfer from turbulence components, the relation between zonal flows and turbulence can make an interpretation with the predator-prey relation [5]. Using T and $\sqrt{Z}$, the Lotka-Volterra equations represent the populations of the predator and prey,

$$\frac{\mathrm{d}T}{\mathrm{d}t} = aT - bT\sqrt{Z},$$

$$\frac{\mathrm{d}\sqrt{Z}}{\mathrm{d}t} = cT\sqrt{Z} - d\sqrt{Z}.$$

From these simultaneous ordinary differential equations, we get the expressions for T and $\sqrt{Z}$,

$$T(\sqrt{Z}, \mathrm{d}\sqrt{Z}/\mathrm{d}t) = \frac{1}{c}\left(d + \frac{1}{\sqrt{Z}}\frac{\mathrm{d}\sqrt{Z}}{\mathrm{d}t}\right),$$

$$\sqrt{Z}(T, \mathrm{d}T/\mathrm{d}t) = \frac{1}{b}\left(a - \frac{1}{T}\frac{\mathrm{d}T}{\mathrm{d}t}\right).$$

If we choose a certain cut-off frequency, 0.1 $[R_0/v_{t_\mathrm{i}}]$, of the low-pass filter, these equations can reproduce the simulation data with errors less than 20 %. Here R_0 and v_{t_i} represent the major radius at the magnetic axis and thermal speed, respectively. This indicates that we can express the oscillatory behavior of turbulence and zonal flow components as the Lotka-Volterra-like equations.

References

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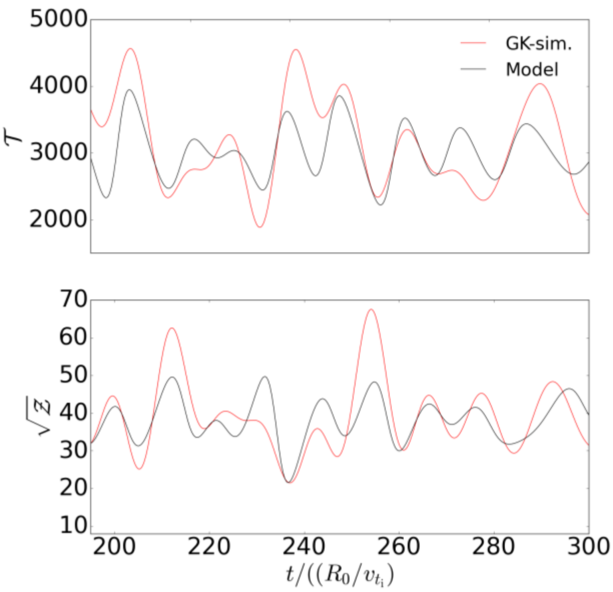

Figure: Comparison between simulation data and predator-prey model with low-frequency components.