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Causal relationship from multivariate time series and dominant scale for ITG turbulent transport

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The relation between plasma turbulence and zonal flows is expected to be a key to understanding turbulent transport in magnetically confined plasmas. Gyrokinetic simulations can evaluate the behavior of fluctuations and turbulent transport quantitatively. Some studies have explained the energy transfer between the fluctuations via nonlinear interactions as predator-prey dynamics[1,2].

We presented that the binding structure constructed in the parameter space spanned by the amplitudes of turbulence T, zonal flow Z, and ion heat diffusivity $\tilde{\chi}_{\mathrm{i}}$ [3] demonstrates predator-prey-like oscillation for the ion temperature gradient (ITG) turbulence with GKV code[4]. In our study, the Lotka-Volterra equation system can explain the energy transfer between fluctuations in the low-frequency region where the coherence between fluctuations is high for several simulation conditions. Our model of the binding structure includes the physics underlying the turbulent transport, although it is difficult to clarify the relation among the three variables. Therefore, we analyze that from the viewpoint of an information criterion. The components of the multivariate reduced auto-regressive (RAR) model provide a directed network of the time series data[5].

The RAR model is a statistical model employed to obtain linear periodic structures. We construct the RAR model for the time series data generated by a nonlinear gyrokinetic simulation to investigate the important time delay for transport modeling. The model for the i-th variable is given by

$$x_i(t) = \sum_{k\in K_{x_i}} A_{x_i,k} T(t-l_k) + \sum_{k\in K_{x_i}} B_{x_i,k} Z(t-l_k) + \sum_{k\in K_{x_i}} C_{x_i,k} \tilde{\chi}_{\mathrm{i}}(t-l_k), \quad (1)$$

where k is an index of time delay, and $A_{x_i,k}$, $B_{x_i,k}$, and $C_{x_i,k}$ are the coefficients with $x_i \in \{T, Z, \tilde{\chi}_{\mathrm{i}}\}$.
It clarifies that the relation between the fluctuations can improve the model performance when turbulence leads to zonal flows.

Furthermore, we investigate a better spatial structure. Conventionally, the amplitudes of turbulence and zonal flow have been defined by spatial integration represented by

$$T = \frac{1}{2}\sum_{k_x,k_y\neq 0} \langle \left|\tilde{\phi}_{k_x,k_y}\right|^2 \rangle_z, \quad (2)$$

$$Z = \frac{1}{2}\sum_{k_x} \langle \left|\tilde{\phi}_{k_x,k_y=0}\right|^2 \rangle_z, \quad (3)$$

where $\tilde{\phi}$ and $\langle\cdots\rangle_z$ denote the electrostatic potential perturbation and flux-average, respectively. However, it was mentioned that the amplitude of zonal flow might change the perpendicular spectrum of turbulence[6]. The extended binding structure in the higher parameter space shows better predictability without the zonal flow amplitude, as shown in the figure. It is a clue to controlling the shear effect of zonal flows and turbulent transport.

References
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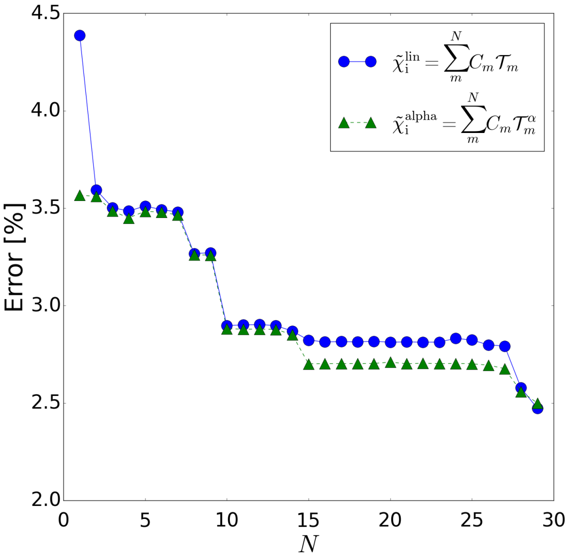

Figure 1. Model performance against fraction size, N. Here, we part T into N sets of the k_y component, $\sum T_m = T$. The models $\tilde{\chi}_{\mathrm{i}}^{\mathrm{lin}}$ (blue circle) and $\tilde{\chi}_{\mathrm{i}}^{\mathrm{alpha}}$ (green triangle) tend to improve the predictability as the fraction size increases.