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Impact of sheared flows on the fractional transport dynamics in a simple fluid drift-wave turbulence model

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It is well known that the action of a sheared flow on turbulence reduces the turbulent transport flux. It has been long accepted that under certain conditions this can be explained by a reduction of the effective turbulent transport coefficients (for instance, the eddy diffusivity) via one or more mechanisms. These mechanisms include the decorrelation of eddies by the sheared flow [1] or the decorrelation of transport events over scales longer than the characteristic eddy size [2] in addition to a reduction of transport from a shift in the cross-phase between the advecting and advected fields. In this paper we show that the effect of the presence of the sheared flow can go beyond the reduction of effective transport coefficients by changing the very nature of the transport dynamics. If the nature of the transport is changed, it calls into question the use of diffusive type models for transport and suggests the need for a new type of transport paradigm. The simulations are carried out with a simple spectral turbulence code in periodic slab geometry, in order to isolate the dynamical effects from complications related to geometry, profile effects and other aspects of the system that can impact the transport characteristics. The results from this study are likely to be relevant to the understanding of transport in simple as well as more complicated situations, neutral fluid as well as plasmas, such as those encountered in gyrokinetic [3] and fluid tokomak turbulence simulations as well as other systems with turbulence and sheared flows.

It is clear that this is of particular importance in magnetically confined plasms such as those found in tokamaks and stellarators in which both externally-driven and self-consistently generated (by the turbulence itself) sheared flows both exist and are crucial for the formation of transport barriers.

To explore both the change in dynamics and the mechanisms behind this change we utilize a simple 1-field model equation for the electrostatic potential ϕ (effectively the stream function). The model used has a slab geometry with a uniform magnetic field (along z), with dissipative trapped electrons and fluid ions and has been used to explore the turbulent dynamics of interacting nonlinearities in the past [4,5]. In this paper we will utilize the model with only the polarization drift nonlinearity. Results with both nonlinearities will be presented elseware. Externally-driven flows can be easily included by adding an external electric potential to ϕ. Because of the periodicity constraints we do this by simply adding a constant kx=0, ky=1,-1 component. We then follow tracer particles as the turbulence evolves to investigate the transport dynamics of the system. The potential and velocity field at one instant in time for a moderate external sheared flow are shown in Fig. 1. The left figure shows the total potential and flow field while the right side shows the same quantities with the external component subtracted out. At this time, one can see a strong vortex that ultimately persists for some time before being decorrelated. The maxima in the shear are at approximately y=0.25 and 0.75.

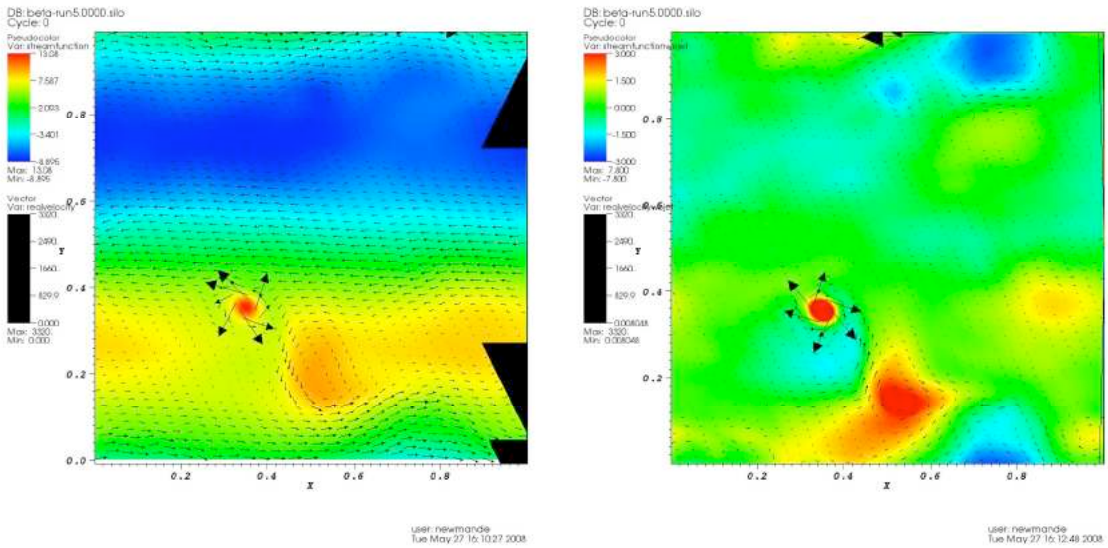

Figure 1. The stream function and velocity field for a case with a moderate sheared flow: (left) with the external flow included; (right) with the external flow subtracted out.

Details of the impact of the sheared flow can be more readily seen in figure 2 which shows a time slice of the vorticity field (the curl of the velocity) for a case with a very small external sheared flow (left) and a moderate sheared flow (right). This figures show a number of important characteristics. With the shear, the radial (y) size of the eddies is reduced while the poloidal (x) size is increased. The eddies are tilted in the direction of the shear and the dominant vorticity of the eddies is consistent with the local vorticity of the sheared flow (ie blue or negative on the top and red or positive on the bottom).

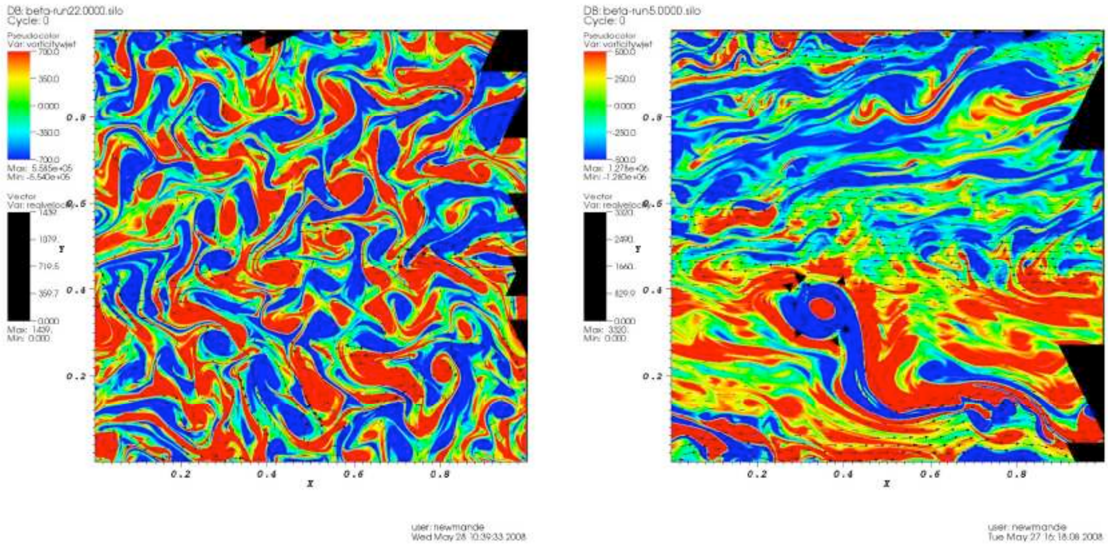

Figure 2. Time slices of the vorticity field: (left) a small external sheared flow showing little effect from from the flow; (right) a moderate external sheared flow showing distortions from the sheared flow.

As the tracer particles move with the flow field, in the unsheared system their lagragian velocities are consistent with a Gaussian random walk (figure 3 left). With a sheared flow however, the x velocities become more ballistic and the y velocities become more anti correlated (figure 3 right).

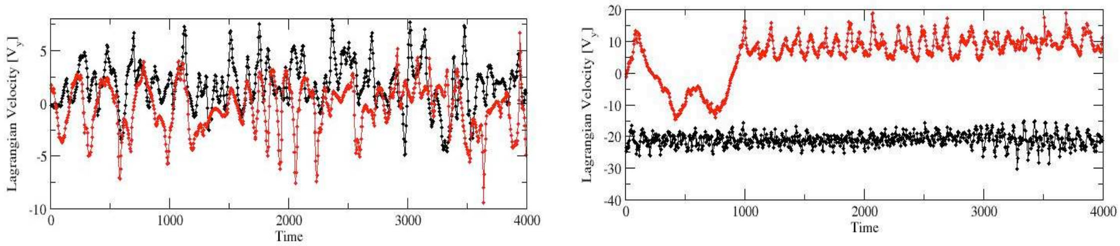

Figure 3 (left) two traces of the lagrangian velocities with no sheared flow; (right) with a moderate sheared flow.

A mechanism for this behaviour is:

1. The presence of a external sheared jet “stretches” those eddies with the same vorticity as the jet, and “cancels” those eddies with opposite vorticity. This leads to an in-out anti-persistent behaviour as particle sample eddies with the same vorticity sign.
2. The “stretching” and tilting of the dominant eddies is such that they are tilted in the direction of increase of the shear of the flow, which also slows down transport in the perpendicular direction through both the in-out anti-persistent behaviour and a phase effect between Vx and Vy which makes jumps to the up motion more likely after a down motion due to the overlap of the tilted eddies.

This effect is clearly observed in the Hurst exponent of the x and y components of the velocity as shown in figure 4. The Hurst exponent gives a measure of the, scale free, persistence (1>H>0.5) or the anti-persistence (0.5>H>0) of a time series [6]. As the shear amplitude is increased, the x velocities become more persistent, approaching ballistic motion characterized by H=1, while the y velocities become anti-persistent appearing to saturate at around H~0.2.

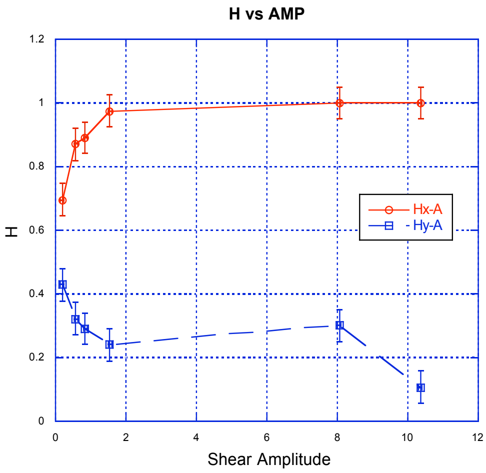

Figure 4 The Hurst exponent for the x and y components of the lagrangian velocity as a function of the shear flow amplitude.

Clearly, the nature of radial turbulent transport changes radically in the presence of a sheared flow. In this case the flow is driven externally, but a similar result is found with a self-consistently driven flow. To appreciate the importance of this, one must to realize that sub-diffusion transport is an example of a system in which characteristic transport scales are absent. *This means that the transport through a sheared flow is likely not describable in terms of classical diffusion*.

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