CLUSTERING OF PARTICLES DRIVEN BY SALINITY GRADIENTS IN TURBULENCE

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Abstract Experimental analysis of the diffusiophoretic effect in turbulence demonstrates that preferential concentration of particles driven by the combined action of turbulence and inhomogeneous distribution of salinity exists. Additionally, theoretical predictions on the distribution of diffusiophoretic particles could be confirmed. We provide evidence that inhomogeneous salt distributions in turbulence produce particle clustering in fractal sets at scales below the Kolmogorov scale. This clustering mechanism may provide the key to understanding a multitude of processes such as formation of marine snow in the ocean and population dynamics of chemotactic bacteria.

INTRODUCTION AND THEORY

Preferential concentration of particles in turbulence plays an important role in a wide range of phenomena in nature as well as industry. The origin of the preferential concentration is the particle drift with respect to the fluid. One of the widest-known phenomena where preferential concentration due to particle drift in turbulence plays a significant role, is the formation of rain in liquid clouds. Thus it is natural to inquire whether preferential concentration would be relevant in the analogous phenomenon in the ocean, which is the formation of marine snow. This occurrence arises due to coagulation of organic matter that results in snow-like precipitation, serving as important deep sea nutrient supply. However, in this case the particle drift may not be caused by inertia, as it does for droplets in clouds, but rather by the inhomogeneous distribution of salinity and the resulting diffusiophoretic effect. Diffusiophoresis is the drift of a colloidal particle in a solution in response to a gradient of the concentration C of a molecular solute [1, 2].

An inclined gravity current was chosen as experimental setup to analyze the diffusiophoretic effect in turbulent flows. The facility allows us to reproduce a turbulent flow that features local gradients of salinity. We simultaneously use 3D particle tracking velocimetry (3D PTV) and laser induced fluorescent measurements (LIF) to obtain the full Lagrangian velocity as well as the local salt concentration in a 3D domain (see further details in [3]). Theory predicts that diffusiophoretic particles cluster in turbulence. In order to check this we studied a turbulent mixture of water and sodium chloride. The particle pair correlation function $\langle n(0)n(\boldsymbol{r})\rangle$ that enters the collision kernel, determining the rate of coagulation of colloids plays the central role in analyzing clustering of particles. The use of the results of Fouxon et al. [4] in our case gives

$$\langle n(0)n(\boldsymbol{r})\rangle = \langle n\rangle^2 \left(\frac{\eta}{r}\right)^{2D_{KY}}, \tag{1}$$

where n is the particle concentration, η is the Kolmogorov scale and D_{KY} is the constant Kaplan-Yorke codimension [4]. This dimension determines the degree of clustering. The drift velocity v_d of diffusiophoretic particles in electrolyte solutions is determined as $\boldsymbol{v}_d \approx D_p \nabla \ln C$, with D_p as the diffusiophoretic constant [2]. Calculating the Kaplan-Yorke codimension can be done directly by using the divergence of the drift velocity ∇v_d of the diffusiophoretic particles

$$D_{KY} = \frac{D_p^2}{|\lambda_3|} \int_0^\infty \langle \nabla^2 \ln C(0) \nabla^2 \ln C(t)\rangle dt \tag{2}$$

where $|\lambda_3|$ is the third of the Lyapunov exponents λ_i, that determines the logarithmic rate of growth of infinitesimal areas of the fluid $S(t)$ by

$$|\lambda_3| = \lim_{t\to\infty} \frac{1}{t} \ln \frac{S(t)}{S(0)}, \tag{3}$$

using that due to incompressibility $|\lambda_3| = \lambda_1 + \lambda_2$. Our experimental analysis resulted in $1/\lambda_3 = 1.2\,\tau_\eta$.

RESULTS AND CONCLUSION

One approach to determine clustering uses the measured 3D Lagrangian velocity field in combination with the local salt concentration to determine the Kaplan-Yorke co-dimension directly by integrating $\langle \nabla^2 \ln C(0) \nabla^2 \ln C(t)\rangle$ along the particle trajectories (Eq. 2). For this analysis the logarithm of the salt concentration field is needed along the trajectories. A 2D snapshot of the $\nabla \ln C$ field, obtained by LIF measurements is displayed in Fig.1. The gradient of this quantity is analyzed along the particle trajectories.

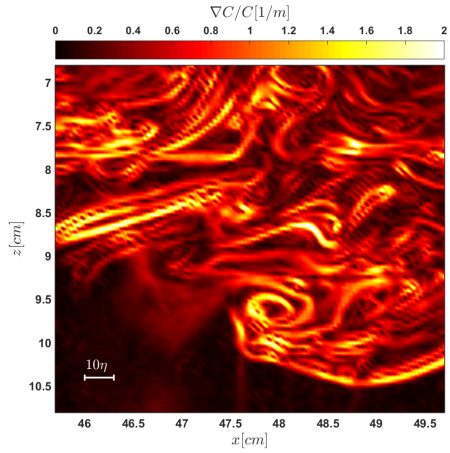

Figure 1. 2D snapshot in the central plane of the observation volume. Showing the gradient of the concentration divided by concentration which is equivalent to $\nabla \ln C$

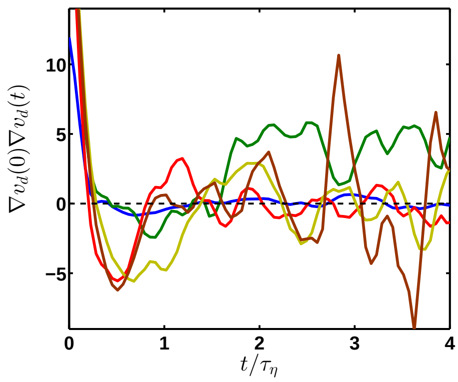

Figure 2. Correlation function of the particle velocity divergence ($\nabla^2 \ln C$) plotted for various trajectories. The dashed lines indicates where the correlation becomes 0 and thus entirely uncorrelated. These correlations are then averaged and integrated to obtain D_{KY}.

The behavior of the correlation function of $D\nabla^2 \ln C$ along various trajectories is shown in Fig. 2. Integrating the average of the correlation function and multiplying with $\frac{D^2}{|\lambda_3|}$ leads to a nonzero Kaplan-Yorke codimension which thus indicates particle clustering due to diffusiophoresis.

In conclusion this direct approach indicates clustering of particles in fractal sets at scales below the Kolmogorov scale due to inhomogeneous salt distributions in turbulence. Furthermore an analysis of the particle distribution using the radial distribution function (RDF) will be performed to obtain D_{KY} and compared with the results obtained by the presented approach.The importance of the presented findings to the formation of marine snow can be estimated by comparing the experimental flow parameters to those of oceanic flows. The typical value for the energy dissipation ϵ per unit volume per unit time in oceanic flows is $10^{-6}m^2/s^3$. Therefore the Kolmogorov time-scale is $\tau_\eta = \sqrt{\nu/\epsilon} \sim 1s$. Correspondingly $\eta = \nu^{3/4}\epsilon^{-1/4} = \tau_\eta^{3/2}\sqrt{\epsilon} \sim 10^{-3}m$ (in the experiment $\eta \sim 5 * 10^{-4}m$), which gives for the Batchelor scale $l_d \sim 10^{-5}m$, equivalent to what is used in the experiment. The small-scale turbulence of the oceanic flows are well approximated in our experiment which makes it quite likely that these results may have significant impact on our understanding of colloid dynamics in oceanic flows and points to a possible role for coagulation of particles in the formation of marine snow in the ocean.

References

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