EUROPEAN MECHANICS SOCIETY

Colloquium 620

Extreme dissipation and intermittency in turbulence

17 – 19 May 2021, online

Book of Abstracts

TU Delft

Preface

Extreme viscous dissipation rates are critical in many industrial, environmental and astrophysical processes dominated by small-scale turbulence. Despite its importance, there is no suitable theory to explain the Reynolds number scaling of the dissipation PDF, its variance and extremes. Any successful new theory will need to properly account for the intermittency and the development of turbulent flow structures at high Reynolds numbers. However, connecting the recent understanding of turbulent flow structure with the prediction of dissipation extrema in real industrial, environmental and astrophysical applications remains a significant challenge and opportunity.

The aim of this EUROMECH colloquium is to bring together scientists from different disciplines (fluid mechanics, turbulence, atmospheric sciences, astrophysics) to discuss the key questions and issues confronting the field. These include: What are the turbulent flow structures relevant to dissipation and how do they depend on the Reynolds number? And, how do these insights in flow structure lead to new theories for the dissipation extremes and intermittency? Moreover, the important implications of intermittency for turbulent dispersion, atmospheric studies and astrophysics are considered. The study of extreme events also offers insight in some fundamental issues associated with the Navier-Stokes equations, such as the irreversibility and smoothness of its solutions.

We look forward to the discussions and thank the authors, invited speakers and session chairs for their contributions and help. The support of EUROMECH is gratefully acknowledged.

Delft, May 7, 2021

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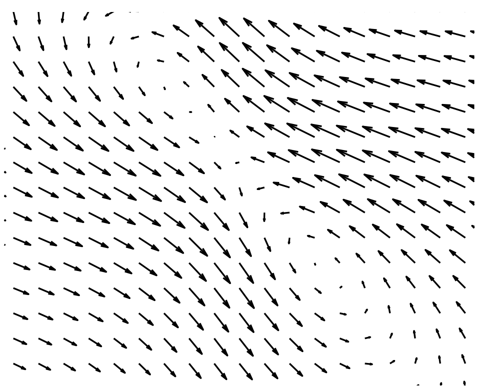

Invited speakers

Luca Biferale (University of Rome - Tor Vergata, Italy)

Statistical properties of turbulence in the presence of a smart small-scale control

Bérengère Dubrulle (Université Paris-Saclay, CEA and CNRS, France)

Experimental and numerical investigations around the 4th Millenium problem (Navier-Stokes existence and smoothness)

Takashi Ishihara (Okayama University, Japan)

Significant thin shear layers in high Reynolds number turbulence

Eliezer Kit (Tel Aviv University, Israel)

Studying of intermittency and bursting phenomena in stratified boundary layer using probability density functions

Alain Pumir (Ecole Normale Supérieure de Lyon and CNRS, France)

Structure and scaling of extreme events in turbulence

P.K Yeung (Georgia Institute of Technology, USA)

Extreme events and extreme computing in turbulence

Programme

all times are Central European Summer Time (local time in Delft)

Monday 17 May 2021

session 1: extreme events and related flow structures

chair: G. Elsinga

9:20	Opening address	
9:30	Structure and scaling of extreme events in turbulence	Alain Pumir, Dhawal Buaria & Eberhard Bodenschatz
10:10	Flow structure dynamics with extreme dissipation events in homogeneous turbulence – An experimental investigation using Shake-The-Box and Flowfit	Andreas Schröder, Daniel Schanz, Sebastian Gesemann, Florian Huhn, Daniel Garaboa Paz & Eberhard Bodenschatz
10:30	*coffee break*	

chair: G. Elsinga

11:00	Connecting boundary layer dynamics with extreme bulk dissipation events in Rayleigh-Bénard flow	Valentina Valori & Jörg Schumacher
11:20	Flow structures govern particle collisions in turbulence	Jason R. Picardo, Lokahith Agasthya, Rama Govindarajan & Samriddhi Sankar Ray
11:40	Study of objective vortical structures in a Von Kármán mixing flow	Farid Aligolzadeh, James R. Dawson & Markus Holzner
12:00	*discussion*	
12:20	*lunch break*	

session 2: analysis through DNS, multifractal and weak solutions

chair: A. Pumir

14:00	Extreme events and extreme computing in turbulence	P.K. Yeung, K. Ravikumar & K.R. Sreenivasan
14:40	Non-local amplification and self-attenuation of extreme events in turbulence	Dhawal Buaria, Alain Pumir & Eberhard Bodenschatz
15:00	Constructing weak solutions in truncated inviscid equations of hydrodynamics: Lessons from the Burgers equation	Sugan D. Murugan, Uriel Frisch, Sergey Nazarenko, Nicolas Besse & Samriddhi Sankar Ray
15:20	*tea break*	

chair: D. Buaria

15:50	Disentangling Lagrangian turbulence	Lukas Bentkamp, Cristian C. Lalescu & Michael Wilczek
16:10	Multiplier distributions and cascade models for enstrophy, dissipation and particle clustering in turbulence	Thomas Hartlep & Jeffrey N. Cuzzi
16:30	Intermittency and thin sets in 3D Navier-Stokes turbulence: A link with the multi-fractal model	J. D. Gibbon
16:50	How close are shell models to the 3D Navier–Stokes equations?	Dario Vincenzi & John D. Gibbon
17:10	*discussion*	
17:30		

Tuesday 18 May 2021

session 3: large scale influences and organization

chair: M. Wilczek

9:10	Significant thin shear layers in high Reynolds number turbulence	<u>Takashi Ishihara</u>, Gerrit E. Elsinga & Julian C. R. Hunt
9:50	Collective vortex organisation in two-dimensional turbulence	<u>Javier Jiménez</u>
10:10	Turbulent structure and intermittency in homogenous isotropic turbulence	<u>Xinxian Zhang</u> & Javier Jiménez
10:30	*coffee break*	

chair: J. Jiménez

11:00	What scales control the evolution of intense events in the dissipative range of isotropic turbulence?	<u>Alberto Vela-Martín</u>
11:20	Extreme dissipation at very high Reynolds number	<u>Gerrit E. Elsinga</u>, Takashi Ishihara & Julian C. R. Hunt
11:40	Helical triad phase coherence in 3D Navier-Stokes turbulence	<u>Miguel D. Bustamante</u> & Brendan P. Murray
12:00	*discussion*	
12:20	*lunch break*	

session 4: intermittency in extreme turbulence (atmosphere, astrophysics and superfluids)

chair: R. Kerswell

14:00	Studying of intermittency and bursting phenomena in stratified boundary layer using probability density functions	Eliezer Kit, Eli Barami, Semion Sukoriansky & Harindra Fernando
14:40	Molecules, magnetic fields and intermittency in cosmic turbulence: Following the energy trail	Edith Falgarone, Thibaud Richard, Pierre Hily-Blant, Alba Vidal-Garcia, Pierre Lesaffre, Benjamin Godard, Andrew Lehmann & Guillaume Pineau des Forêts
15:00	Coherence of extreme dissipation structures in a non-star-forming molecular cloud	Pierre Hily-Blant, Edith Falgarone, Simon Delcamp and the MIST team
15:20	*tea break*	

chair: P.K. Yeung

15:50	Reconnection-controlled decay of magnetohydrodynamic turbulence and the role of invariants	D. N. Hosking & A. A. Schekochihin
16:10	Probing the nature of dissipation extrema in compressible MHD turbulence	Thibaud Richard, Pierre Lesaffre, Edith Falgarone & Andrew Lehmann
16:30	Intermittency of velocity circulation in quantum and classical turbulence	Giorgio Krstulovic, Nicolás P. Müller & Juan Ignacio Polanco
16:50	*discussion*	
17:10		

Wednesday 19 May 2021

session 5: singularity & irreversibility

chair: L. Biferale

9:10	Experimental and numerical investigations around the 4th Millenium problem (Navier-Stokes existence and smoothness)	<u>Bérengère Dubrulle</u>
9:50	Lagrangian irreversibility and intermittent dissipation in turbulence	<u>Jason R. Picardo</u>, Akshay Bhatnagar & Samriddhi Sankar Ray
10:10	Exploration of Lagrangian and Eulerian irreversibility in an experimental Von Kármán flow	<u>Adam Cheminet</u>, Paul Debue, Valentina Valori, Yasar Ostovan, Christophe Cuvier, Jean-Philippe Laval, Jean-Marc Foucaut, François Daviaud & Bérengère Dubrulle
10:30	*coffee break*	

chair: W. Bos

11:00	Identification of turbulent structure in pipe flow using Tomographic PIV	<u>Kovid Bhatt</u> & Yoshiyuki Tsuji
11:20	Time-reversible Navier-Stokes equations	<u>Vishwanath Shukla</u>
11:40	Finite dissipation from helicity following reconnection	<u>Robert M. Kerr</u>
12:00	*discussion*	
12:20	*lunch break*	

session 6: numerical experiments and control

chair: B. Dubrulle

14:00	Statistical properties of turbulence in the presence of a smart small-scale control	Luca Biferale, Michele Buzzicotti & Federico Toschi
14:40	Exploring causality through sensitivity in homogeneous isotropic turbulence	Miguel P. Encinar & Javier Jiménez
15:00	Turbulence without vortex stretching	Tong Wu & Wouter J. T. Bos
15:20	*tea break*	

chair: G. Elsinga

15:50	Predator-prey modeling of large-scale energy fluctuations in turbulence	Ryo Araki, Wouter J. T. Bos & Susumu Goto
16:10	Highly causal events in turbulent channel flow	Kosuke Osawa & Javier Jiménez
16:30	*discussion & close*	
16:50		

Monday 17 May 2021

Session 1

9:20 – 12:20

STRUCTURE AND SCALING OF EXTREME EVENTS IN TURBULENCE

Alain Pumir[1,2], Dhawal Buaria[3,2] & Eberhard Bodenschatz[2,4]
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Fully turbulent flows are characterized by intermittent formation of very intense velocity gradients, which have been demonstrated to have the remarkably simple structure of thin vortex filaments, see the left panel of Fig 1 and [1]. The magnitude of vorticity in these "micro-tornadoes" reaches values considerably larger than its average magnitude, the more so as the Taylor scale Reynolds number, R_λ, increases.

A natural question one may ask is how to characterize these extreme events as a function of the R_λ. To this end, we utilize data from direct numerical simulations (DNS) of isotropic turbulence in periodic domains, with very high spatial and temporal resolution [1] for Taylor-scale Reynolds number R_λ in the range $140 - 650$. Our results show a very good collapse of the long tails of probability density function of enstrophy, $\Omega = |\boldsymbol{\omega}|^2$, see the central panel of Fig. 1, suggesting the extreme vorticity scale with the time scale $\tau_{ext} = \tau_K \times {R_\lambda}^{-\beta}$, with $\beta \approx 0.78$, and $\tau_K = 1/\langle \Omega \rangle^{-1/2}$ being the Kolmogorov time scale, which characterizes the average magnitude of vorticity.

These observed scaling behaviors can be explain in terms of the vortex stretching mechanism, which results from a coupling with the rate of strain, $S_{ij} = 1/2(\partial_i u_j + \partial_j u_i))$. A quantitative understanding of this coupling is obscured by the nonlocal relation between strain and vorticity [2]. Remarkably, our DNS indicate that the average of the magnitude of strain, $\Sigma = 2 S_{ij} S_{ij}$, conditioned on Ω, has a power law dependence: $\tau_K^2 \langle \Sigma | \Omega \rangle \propto (\tau_K^2 \Omega)^\gamma$, where $\tau_K^2 = 1/\langle \Omega \rangle$ is the Kolmogorov time scale, see the right panel of Fig 1. The exponent γ slowly increases with R_λ [1, 3].

Elementary phenomenological considerations allow us to extract a characteristic size, $R(\Omega)$, from the dependence of $\langle \Sigma | \Omega \rangle$. Namely, assuming that the structure of the intense vortices results from a balance between viscosity and strain, one obtains $R(\Omega) \sim (\nu / \Sigma^{1/2})^{1/2} \sim \eta (\tau_K \Omega)^{-\gamma/4}$. Using the relation $\Omega \sim (u'/R(\Omega))^2$, one can deduce self-consistent relation for the most intense vortices: $\Omega \sim \tau_K^{-2} \times {R_\lambda}^{1/(2-\gamma)}$, which in turn suggests the relation $\beta = 1/(2-\gamma)$. The values of β and γ determined numerically are compatible with this relation [1].

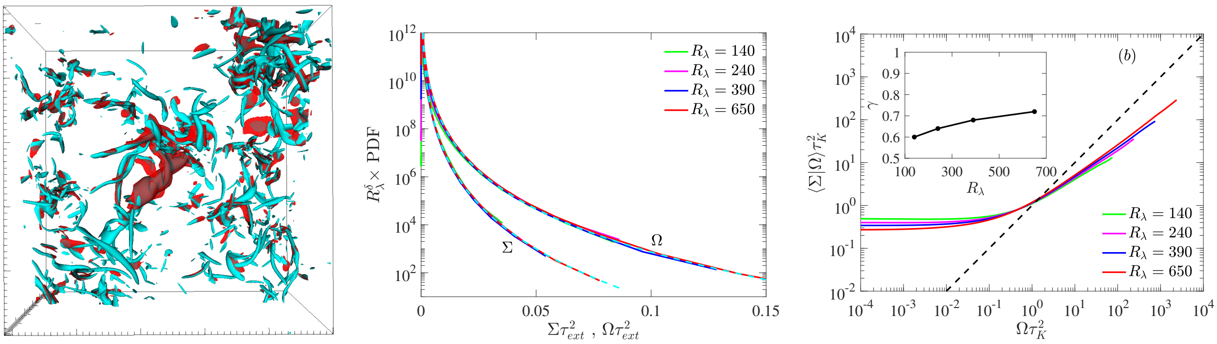

Figure 1. Left: Regions of intense vortices (cyan) and strain (red) in a subdomain of the flow of size $(256\eta)^3$. The iso-values of the fields correspond to $50/\tau_K^2$. Center: the PDF of Ω and Σ, superposed after rescaling, over the range $140 \leq R_\lambda \leq 650$. Right: the strain Σ conditioned on Ω. The inset shows the exponent γ, describing the power law relation: $\langle \Sigma | \Omega \rangle \sim \Omega^\gamma$.

Further insight can be obtained by expressing $\mathbf{S}$ as a Biot-Savart integral, and the local strain, $\mathbf{S}^L$, by restricting the integral to a ball of radius ρ (the nonlocal part satisfying $\mathbf{S}^{NL}$ by: $\mathbf{S} = \mathbf{S}^L + \mathbf{S}^{NL}$). When $\rho \to 0$ ($\rho \to \infty$), $\mathbf{S}^{NL} \approx \mathbf{S}$ ($\mathbf{S}^L \approx \mathbf{S}$). At an intermediate value of ρ, $||\mathbf{S}^L|| = ||\mathbf{S}^{NL}||$. Extending this construction to strain conditioned on vorticity leads to the definition of a characteristic scale $\rho(\Omega)$, which depends on Ω as a power law, with an exponent $\approx \gamma/4$.

The suggested self-similarity of the vortex structure as a function of the intensity of the vorticity breaks down when the size $\rho(\Omega)$ becomes of the order of $\sim 4\eta$. At such small values of R, the contribution to vortex stretching from $\mathbf{S}^L$ becomes *negative*, implying that the local strain, surprisingly, inhibits the amplification of the most intense vorticies [2].

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[2] D. Buaria, A. Pumir, and E. Bodenschatz, *Nat. Commun.* **11**:5852, 2020.
[3] D. Buaria, E. Bodenschatz, and A. Pumir, *Phys. Rev. Fluids* **5**:104602, 2020.

FLOW STRUCTURE DYNAMICS WITH EXTREME DISSIPATION EVENTS IN HOMOGENEOUS TURBULENCE – AN EXPERIMENTAL INVESTIGATION USING SHAKE-THE-BOX AND FLOWFIT

Andreas Schröder[1], Daniel Schanz[1], Sebastian Gesemann[1], Florian Huhn[1], Daniel Garaboa Paz[2] and Eberhard Bodenschatz[3]

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[2] *Group of Non-linear Physics, University of Santiago de Compostela, Spain.*

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Since the introduction of the Richardson-Kolmogorov cascade a picture of turbulence has been created that intrinsically connects a (in general) directional down-scaling process featuring vortical flow structures with the overall energy transfer finally ending into viscous dissipation at the smallest scales of the cascade. In turbulent flows at sufficient Reynolds number intermittency of extreme dissipation events is accompanied by strong enstrophy events and both have a close relationship to the pressure Laplacian. The aim of the present investigation is to analyze the temporal dynamics of flow structures generating extreme dissipation events. Conditional ensemble averages and Lagrangian viewpoints shall complement this topological study.

We present measurements of the full velocity gradient tensor and all elements of the dissipation rate based on dense fields of fluid particle trajectories in homogeneous turbulence at $Re_\lambda \sim 270$ and ~370 in a von Kármán flow between two counter-rotating propellers. Applying the *Shake-The-Box* (STB) particle tracking algorithm [1], we are able to instantaneously track up to ~100.000 particles in a measurement volume of 50 x 50 x 15 mm³. The mean inter-particle distance is lower than 7 Kolmogorov lengths. The data assimilation scheme *FlowFit* [2] with continuity and Navier-Stokes- constraints is used to interpolate the scattered velocity and acceleration data by continuous 3D B-Splines in a cubic grid, enabling to recover (locally) the smallest flow scales. We compute the energy dissipation rate directly by using local velocity gradient information gained by FlowFit at midpoints of particle tetrahedra in close proximity of a few Kolmogorov lengths and compare it to known inertial range approaches using two-point statistics.

The experimental setup at the GTF3 of MPI-DS in Göttingen consists of a cylindrical water tank (500 mm diameter) with two counter-rotating propellers at the top and at the bottom, generating a von Kármán flow with a homogeneous turbulent region in the center (at least in radial directions). From earlier experiments [5], the expected Kolmogorov length for the lower Re_λ is $\eta \sim 100\,\mu$m at a propeller frequency of 0.5 Hz. The Kolmogorov time is $\tau \sim 10$ ms, i.e., temporal oversampling by a factor of 12.5 at 1.25 kHz frame rate. Spherical monodisperse and nearly neutrally buoyant polystyrene particles (20μm diameter) are illuminated by a fibre-coupled 150 W Nd:YAG high frequency laser (IB Chronos 400 MM IC SHG) in the center of the tank. Four CMOS cameras (Phantom v640, 2560 x 1600 pixel, 1250 Hz) equipped with 100 mm Zeiss macro lenses ($f_\#$ = 16) and Scheimpflug adapters record the particles in ~45° forward scattering. Prisms attached to the tank avoid astigmatism of particle images.

We acknowledge funding from the European High-Performance Infrastructures in Turbulence (EuHIT) consortium for the DTrack measurement campaign and the support of the staff at MPI-DS in Göttingen. This work was supported by the *Deutsche Forschungsgemeinschaft* (DFG) through Grant No. SCHR 1165/5-1 as part of the Priority Programme on Turbulent Superstructures (DFG SPP 1881).

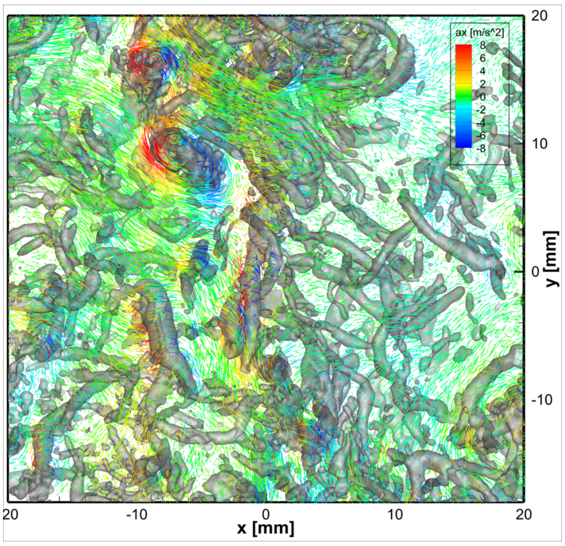

Figure 1. Dense Lagrangian particle tracks measured by STB, color coded by x-component of acceleration and iso-surfaces of Q-criterion, Q= 2500 s^{-2} from FlowFit. $Re_\lambda \sim 270$, Kármán flow at GTF3 at MPI-

References

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CONNECTING BOUNDARY LAYER DYNAMICS WITH EXTREME BULK DISSIPATION EVENTS IN RAYLEIGH-BÉNARD FLOW

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We study the connection between extreme events of thermal and kinetic dissipation rates in the bulk of three-dimensional Rayleigh-Bénard convection and the wall-shear-stress at the top and the bottom boundary layers of the cell. Local minima in the vicinity of zero points of the wall shear-stress vector field are connected to the smallest magnitudes of the vertical temperature derivative in the boundary layer, and identify the locations where thermal plumes rise from the boundary layers [1, 2]. Our direct numerical simulations at Rayleigh number of $Ra = 5 \times 10^5$ and Prandtl number $Pr = 1$ in a Cartesian domain of aspect ratio $\Gamma = 8$ cell show that local maxima of the vertical temperature derivative, which appear simultaneously at similar horizontal positions in both boundary layers, can be considered as a precursor for an extreme event of thermal and kinetic energy dissipation in the bulk of the cell. This scenario requires a breaking of the synchronicity of the boundary layer dynamics at both plates, which is found to be in line with a transition of the bulk derivative statistics from Gaussian to intermittent. Our studies are based on high-resolution direct numerical simulations for moderate Rayleigh numbers between 10^4 and 5×10^5. Figure 1 illustrates the formation of such an event.

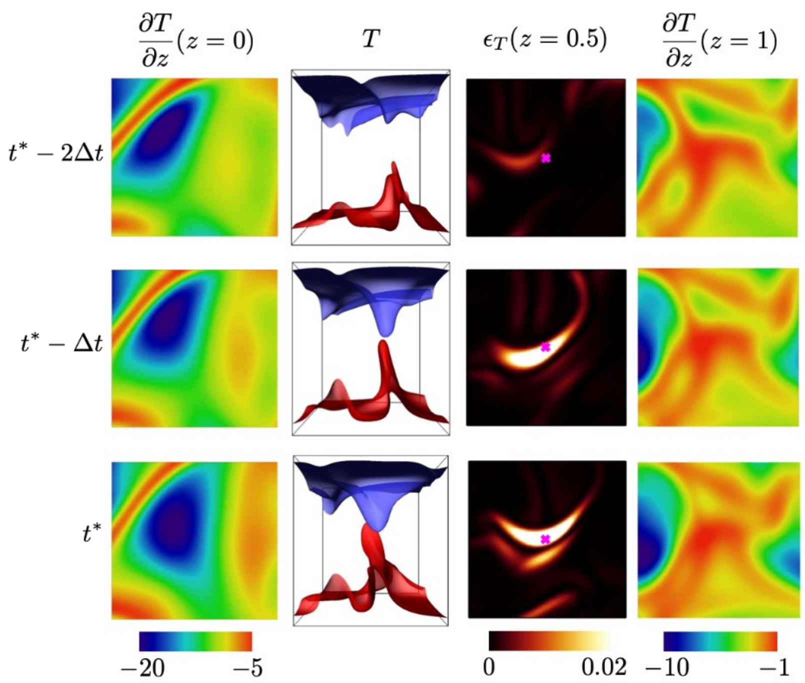

Figure 1. Formation of an extreme thermal dissipation rate event in the centre of the convection layer. The panels in this figure illustrate the dynamical processes at the walls in connection with those in the bulk, which lead to the event. The three rows from top to bottom stand for snapshots of relevant fields at times t^*-2Δt, t^*-Δt, and t^* with t^* the time at which the event occurs and $\Delta t = 0.475$. The quantities that are displayed in the 4 columns are: the vertical derivative of temperature, $\partial T/\partial z$, at $z = 0$, the temperature T across the layer, which is illustrated by two isosurfaces at $T = 0.3$ (blue) and $T = 0.7$ (red), the thermal dissipation rate ϵ_T at $z = 0.5$, and $\partial T/\partial z$ at $z = 1$. The area is always $H \times H$ and $Ra = 5 \times 10^5$. Color bars stand for all panels in a column. The magenta cross on the ϵ_T plots represents the position where the extreme event of ϵ_T occurs.

References

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FLOW STRUCTURES GOVERN PARTICLE COLLISIONS IN TURBULENCE

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The role of the spatial structure of a turbulent flow in enhancing particle collision rates in suspensions is an open question. We show and quantify, as a function of particle inertia, the correlation between the multiscale structures of turbulence and particle collisions: Straining zones contribute predominantly to rapid head-on collisions compared to vortical regions. We also discover the importance of vortex-strain worm-rolls, which goes beyond ideas of preferential concentration and may explain the rapid growth of aggregates in natural processes, such as the initiation of rain in warm clouds.

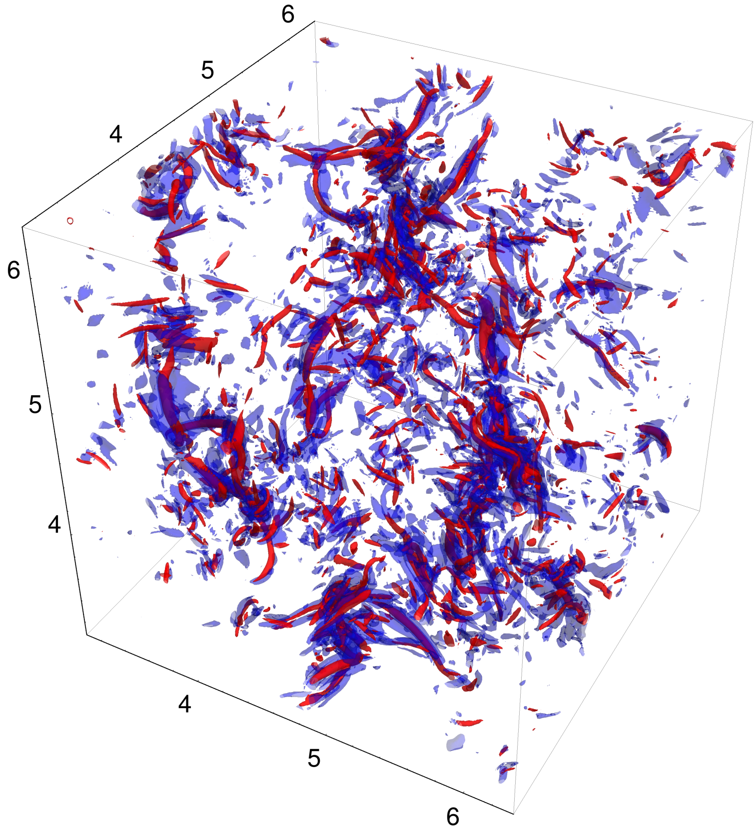

Figure 1. A representative snapshot of three-dimensional contours of $\mathcal{Q}$ showing intense vortex tubes (opaque red: $+5.6\sqrt{\langle \mathcal{Q}^2 \rangle}$) enveloped by dissipative, straining sheets (transparent blue: $-2\sqrt{\langle \mathcal{Q}^2 \rangle}$).

References

[1] This work was published as: *Flow structures govern particle collisions in turbulence* J. R. Picardo, L. Aghasthya, R. Govindarajan, and S. S. Ray, Physical Review Fluids (Rapid), **4**, 032601(R) (2019).

STUDY OF OBJECTIVE VORTICAL STRUCTURES IN A VON KÁRMÁN MIXING FLOW

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A recent method proposed by Haller et al. [1] has been used to identify objective vortical structures in a fully resolved three-dimensional experimental data set of small-scale turbulence measured at the centre of a von Kármán mixing tank at a $Re_\lambda = 179$ [2]. Instantaneous vorticity deviation (IVD) fields are used to objectively define vortical structures without the use of classical thresholding methods to avoid conventional arbitrariness in vortex definition [3]. Different features of the turbulent flow are investigated inside of these structures and compared to the same features for the whole volume of the flow without conditioning. These high enstrophy structures are strongly intermittent and are found to have an average radius of 4.9η, where η is the Kolmogorov length scale. Comparison of the PDFs of enstrophy and dissipation values conditioned on the structures with the whole volume of the flow shows that the structures contain high value events of enstrophy and dissipation and low value events are rare. Comparison of the conditioned and unconditioned J-PDFs of enstrophy and dissipation shows a shift towards the high shear region for the case of the structures. PDFs of alignment ($cos(\theta_i)$) between the vorticity vector and the rate of strain eigenvectors inside the structures illustrate that the vorticity vector is aligned in parallel with the second (intermediate) eigenvector but perpendicular to the first (extensional strain) and the third (compressive strain) eigenvectors. To investigate the flow topology (configuration of streamlines) inside the structures, conditioned and conditioned J-PDFs of the invariants of rate of strain tensor, Q and R, are plotted. The tear-drop shape is observable for both cases but for the case of the structures, high values of J-PDF are shifted towards the top left quarter of the Q-R plane which implies that the vortex stretching is the dominant topology. The entrainment velocity, v_n, and its components are calculated on the boundary of the structures based on a formula derived by Holzner & Lüthi [4] (figure 1.). The results indicate that both entrainment and detrianment happen at the boundary of the structures. However, entrainment is the dominant phenomenon and in total, ambient fluid is entrained into the structures. It has also been observed that vortex stretching is the dominant phenomenon where entrainment happens (negative values of v_n). On the other hand, enstrophy diffusion is the dominant phenomenon where detrainment happens (positive values of v_n).

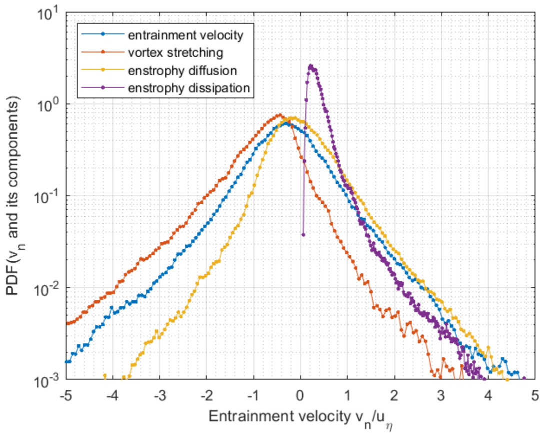

Figure 1. PDFs of entrainment velocity and its components.

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Monday 17 May 2021

Session 2

14:00 – 17:30

EXTREME EVENTS AND EXTREME COMPUTING IN TURBULENCE

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Widely-held interests in the detailed characterization of extreme events in highly intermittent turbulent flow [1, 2] have provided major motivation towards ever-larger simulations of isotropic turbulence, where the bulk of advanced computational power is spent on meeting resolution requirements in both space and time, at levels more stringent [3, 4] than often thought in the past. Recent work at grid resolution up to 18432^3 enabled by advanced techniques in GPU computing [5] has allowed us to clarify, for instance, the similarities and differences in the scaling behaviors of dissipation and enstrophy, taken at a point as well as averaged locally in three dimensions over scale sizes ranging from the dissipation range to the inertial range, as shown in Fig. 1 below (from [6]).

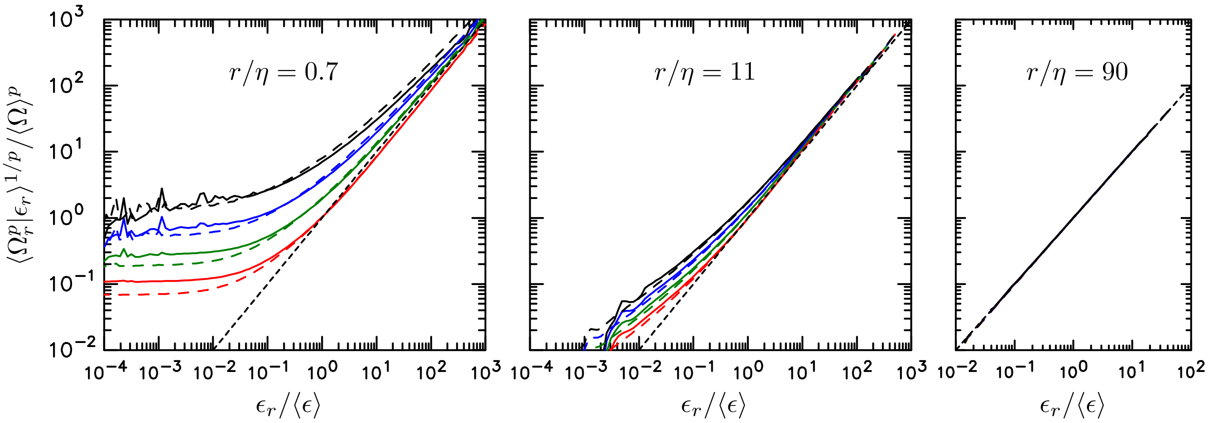

Figure 1. Conditional moments of orders 1,2,3,4 (in red, green, blue, black) of 3D local averages of enstrophy given dissipation, in different ranges of linear size r. Solid lines from simulations at $R_\lambda \approx 390$ and dashed lines from $R_\lambda \approx 1000$. Dashed line of slope 1 corresponds to the scenario enstrophy and dissipation scaling jointly in the same manner.

In this talk we will present the main elements of GPU computing for pseudo-spectral simulations of 3D turbulence, as well as a new "multi-resolution independent simulations" (MRIS) approach that allows well-sampled results at high small-scale resolution to be achieved at much lower cost compared to full-length simulations at such resolution. We then report briefly on current work where high-resolution simulation data are being used to provide further insights on other aspects of intermittency. The first of these is the nature of extreme fluctuations of the scalar dissipation rate that arise in turbulent mixing. The second is the use of data on 3D local averages for a re-examination of multifractal spectra where prior results in the literature were mostly based on averages in 1D only.

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NON-LOCAL AMPLIFICATION AND SELF-ATTENUATION OF EXTREME EVENTS IN TURBULENCE

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Fully turbulent fluid flows, described by the three-dimensional incompressible Navier-Stokes equations, are characterized by intermittent generation of intense velocity gradients, which play a crucial role in many natural and engineering processes [1, 2]. These extreme events are known to be arranged in tube-like vortical structures and their amplification is readily described via the vortex stretching mechanism, which expresses the non-linear coupling between vorticity and the strain-rate tensor [3]. An essential aspect of this coupling is non-locality, whereby vortex stretching in one region of space is affected by the entire flow field, resulting in outstanding mathematical challenges in turbulence theory and also establishing the regularity of Navier-Stokes equations. Quantitatively, this non-locality can be expressed by writing the strain-rate tensor $\mathbf{S}(\mathbf{x})$ as a global Biot-Savart integral over the vorticity field $\omega(\mathbf{x})$:

$$S_{ij}(\mathbf{x}) = \frac{3}{8\pi} \int_{\mathbf{x}'} (\epsilon_{ikl} r_j + \epsilon_{jkl} r_i)\, \omega_l(\mathbf{x}')\, \frac{r_k}{r^5}\, d^3\mathbf{x}' \,, \tag{1}$$

and essentially couples all the scales in the flow. To analyze the non-locality with respect to a scale size R, the strain at each spatial point can be decomposed as [4]: $S_{ij}(\mathbf{x}) = S^{\rm L}_{ij}(\mathbf{x}, R) + S^{\rm NL}_{ij}(\mathbf{x}, R)$, where $\mathbf{S}^{\rm L}$ is the local contribution, obtained by evaluating the Biot-Savart integral in the neighborhood $r \leq R$, and $\mathbf{S}^{\rm NL}$ is the non-local contribution over the background $r > R$. While these contributions cannot be evaluated analytically, we have recently devised a method to accurately and efficiently determine these contributions from direct numerical simulations (DNS) [5] – which is the basis of the current work. Utilizing DNS of isotropic turbulence in periodic domains of up to 12288^3 grid points, and Taylor-scale Reynolds number R_λ in the range $140 - 1300$, we investigate the non-locality of vorticity amplification, focusing on extreme events by conditioning statistics on enstrophy, $\Omega = \omega_i \omega_i$. Our results demonstrate that vorticity is primarily amplified through non-local strain, similar to linear dynamics of stretching of passive material lines. This is in particular evident from alignment properties of vorticity and non-local strain tensor, shown in Fig. 1a-b. However, as vorticity is amplified beyond a threshold, the locally induced strain acts non-linearly to counteract this amplification [5], shown in Fig. 1c. This non-local amplification and subsequent self-attenuation sheds new light on the non-trivial small-scale structure of turbulence and could provide a direction in establishing the regularity of Navier-Stokes equations.

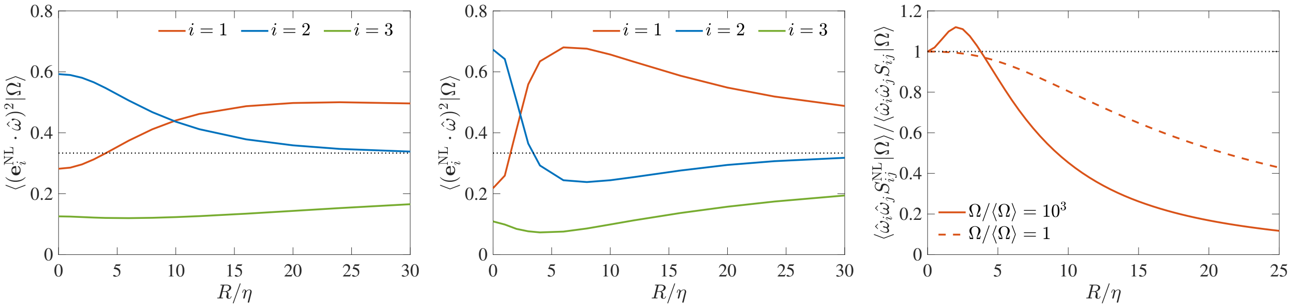

Figure 1. Alignment cosines between vorticity ω_i and eigenvectors of non-local strain $\mathbf{e}_i^{\rm NL}$, as function of R/η, at $R_\lambda = 1300$. The alignments are conditioned on enstrophy $\Omega = \omega_i\omega_i$ for (a) $\Omega/\langle\Omega\rangle = 1$ and (b) $\Omega/\langle\Omega\rangle = 10^3$. Vorticity preferentially aligns with the first (extensive) eignevector beyond a certain R/η, which decreases as Ω increases. (c) The conditional non-local stretching rate as a fraction of total stretching rate, as a function of R/η at $R_\lambda = 1300$. At large Ω, the fractional non-local stretching is greater than unity for small R, suggesting the local stretching is negative.

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CONSTRUCTING WEAK SOLUTIONS IN TRUNCATED INVISCID EQUATIONS OF HYDRODYNAMICS: LESSONS FROM THE BURGERS EQUATION

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Finite-dimensional, inviscid equations of hydrodynamics, obtained through a Fourier-Galerkin projection, thermalize with an energy equipartition. Hence, numerical solutions of such inviscid equations, which typically must be Galerkin-truncated, show a behavior at odds with the parent equation [4, 3, 1, 2]. An important consequence of this is an uncertainty in the measurement of the temporal evolution of the distance of the complex singularity from the real domain leading to a lack of a firm conjecture on the finite-time blow-up problem in the incompressible, three-dimensional Euler equation. We now propose, by using the one-dimensional inviscid Burgers equation as a testing ground, a numerical recipe, named tyger purging, to arrest the onset of thermalization [5, 4] and hence recover the true dissipative solution (which can be obtained otherwise analytically in the vanishing viscosity limit). Our method, easily adapted for higher dimensions, provides a tool to not only tackle the celebrated blow-up problem but also to obtain weak and dissipative solutions—conjectured by Onsager and numerically elusive thus far—of the Euler equation.

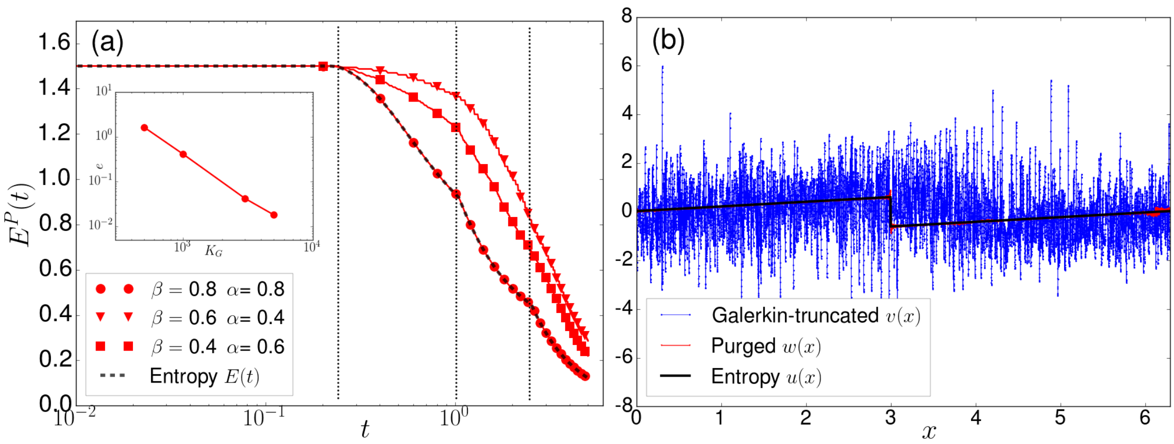

Figure 1. (a) Energy of the weak solution to Burgers obtained through purging, (b) Velocity profile in different cases

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DISENTANGLING LAGRANGIAN TURBULENCE

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Particles in turbulence frequently encounter extreme accelerations between extended periods of mild fluctuations. The occurrence of extreme events is closely related to the intermittent spatial distribution of intense flow structures. For example, as illustrated in fig. 1(left), vorticity filaments can give rise to acceleration events exceeding the root-mean-squared fluctuations by orders of magnitude [1, 2]. The mixed history of flow conditions along Lagrangian trajectories implies a pronouncedly scale-dependent statistics with extreme fluctuations on small temporal scales [3, 4, 5]. This phenomenon, known as Lagrangian intermittency, presents one of the major challenges on the way to a statistical theory of turbulence. In this contribution, we introduce the notion of persistent Lagrangian acceleration, which we measure by coarse-graining the squared acceleration over a typical viscous time scale: $\alpha(t) \equiv \int_{-\infty}^{\infty} F_\Theta(\tau)\, \boldsymbol{a}^2(t+\tau)\, \mathrm{d}\tau$. Here, $\boldsymbol{a}(t)$ denotes the acceleration vector along a Lagrangian trajectory and $F_\Theta(\tau)$ a Gaussian filter kernel with standard deviation Θ, which we choose on the order of a few Kolmogorov time scales. Conditioning Lagrangian particle data from direct numerical simulations on this coarse-grained acceleration, we find remarkably simple, close-to-Gaussian statistics for a range of Reynolds numbers. As an example, fig. 1(right) shows the acceleration PDFs conditional on α. In the spirit of the Lagrangian refined similarity hypothesis, this opens the possibility to decompose the complex particle statistics into much simpler sub-ensembles. Based on this, we develop a comprehensive theoretical framework for Lagrangian single-particle statistics that captures the acceleration, velocity increments as well as single-particle dispersion [6].

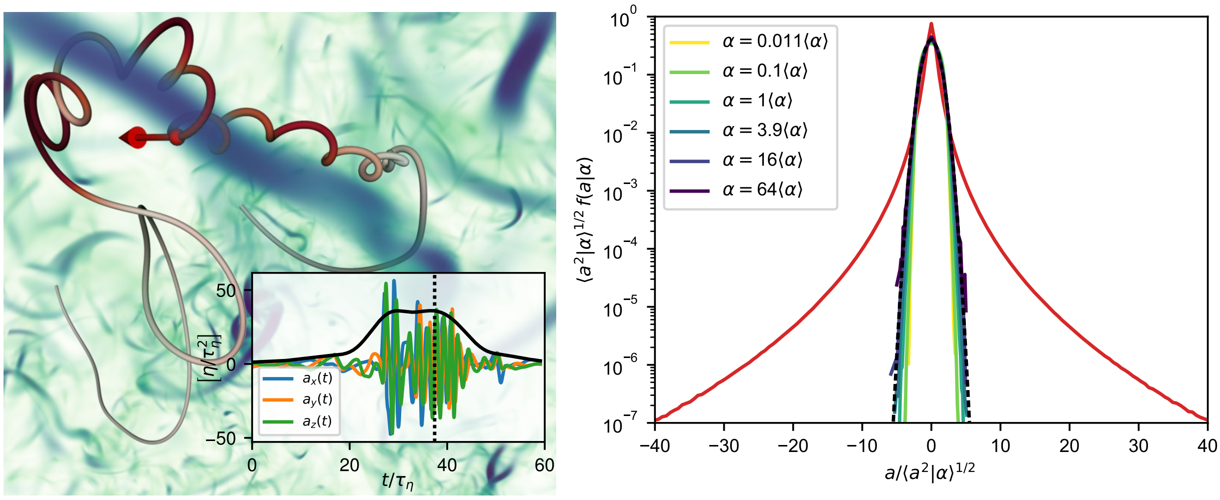

Figure 1. Left: The acceleration components of a tracer particle encountering an intense vortex (blue volume rendering) oscillate strongly in time (inset). The root of the squared acceleration, coarse-grained over a few Kolmogorov time scales, only varies weakly during such an event (inset, black curve). **Right:** The acceleration PDFs conditional on α (colored lines) are all close to Gaussian. The unconditional acceleration PDF (red, solid line) and a Gaussian distribution (black, dashed line) are plotted for comparison.

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MULTIPLIER DISTRIBUTIONS AND CASCADE MODELS FOR ENSTROPHY, DISSIPATION AND PARTICLE CLUSTERING IN TURBULENCE

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The notion of a turbulent cascade is most often understood as the flow of kinetic energy, injected at some large scale, down to smaller and smaller scales through the breakdown of turbulent eddies. In the inertial range of homogenous, isotropic turbulence, where this process is scale invariant, this cascade of energy leads to Kolmogorov's famous results of a $-5/3$ slope of the kinetic energy spectrum of [1]. More general cascade models can be constructed for any quantity in the flow [2–9] where stochastic partition functions or *multipliers* $0 \leq m \leq 1$ are used to describe how a quantity is subdivided to progressively smaller scales. In high Reynolds number atmospheric boundary layer experiments [7] it was shown that the multiplier distributions for dissipation are independent of scale (within the inertial range) and approximately follow symmetric β distributions with a shape parameter $\beta \simeq 3$.

We [9] have used data from a numerical simulation of particle-laden turbulence at a Taylor-scale Reynolds number of $Re_\lambda \sim 400$ [10] and have measured multiplier distributions for dissipation and enstrophy (Figure 1) as well as particle density, finding that dissipation and enstrophy multipliers do indeed reach scale independence albeit at larger values of β (corresponding to narrower distributions) than seen in the much higher-Re atmospheric experiments mentioned above. For the clustering of particles, we have found that the multiplier distributions for particle density are *not* independent of scale but approximately collapse to a single curve when appropriately scaled. Cascade models can be built by applying such multipliers successively to smaller and smaller scales, and can be used to predict the probability distributions of dissipation, enstrophy and particle density at any scale in the inertial range. Such models have been used, for instance, to predict the sizes and formation probability of the first primitive asteroids in the protoplanetary disk through gravitational sedimentation of regions overdense in solids [11]. In this talk we will review some of the findings of [9], including speculations for higher-Re flows inaccessible to numerical simulations.

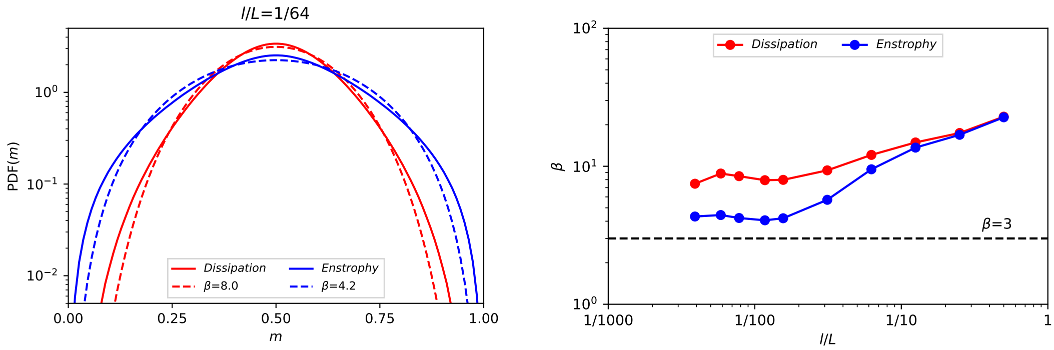

Figure 1. *(Left panel)* Multiplier distributions for dissipation and enstrophy determined from a numerical simulation at a scale of $l/L = 1/64$ where L is the integral scale of the turbulence and l is the particular binning scale used. Solid curves show the measured probability distribution functions (PDF) while the dashed curves show corresponding β distributions with the same widths as the PDFs. *(Right panel)* Shape parameter β of corresponding β distributions for dissipation and enstrophy as functions of scale as determined from the numerical simulation.

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INTERMITTENCY AND THIN SETS IN $3D$ NAVIER-STOKES TURBULENCE : A LINK WITH WITH THE MULTI-FRACTAL MODEL

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Visual manifestations of intermittency in computations of three dimensional Navier-Stokes fluid turbulence appear as low-dimensional or 'thin' filamentary sets on which vorticity and strain accumulate as energy cascades down to small scales [1, 2, 3, 4, 5, 6, 7]. This process occurs through the multiple flattening and subsequent filamentation of initial states which end in a tangle of quasi-one-dimensional fine-scale vortex tubes (see a typical example in figure 1). Structures of dimension less than unity have recently been reported [7]. A moot question is why the trend towards low-dimensionality appears to be a universal phenomenon. My first task is to investigate how weak solutions of the Navier-Stokes equations can be associated with a cascade and, as a consequence, with an infinite sequence of inverse length scales which converge to a finite limit. How these results scale with the dimension d suggests that low-dimensional accumulation occurs because of a need to find the most dissipative sets rather than the most singular [8].

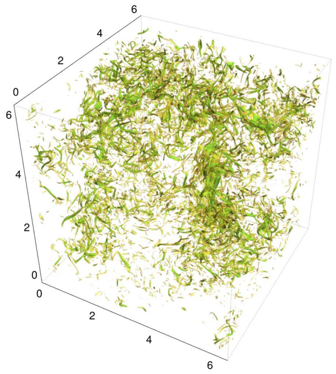

Figure 1. A snapshot of the energy dissipation field $\varepsilon = 2\nu S_{i,j}S_{j,i}$ of a forced 512^3 Navier-Stokes flow at $Re_\lambda = 196$ which is colour-coded such that yellow is 4 times the mean & blue denotes 6 times the mean. Plot courtesy of J. R. Picardo (IIT Mumbai) and S. S. Ray (ICTS Bangalore).

The concept of accumulation on low-dimensional sets has been reinforced by some recent work by the author, in collaboration with Berengere Dubrulle, which has shown that there exists a correspondence between the multifractal model of turbulence and the set of Navier-Stokes length scales discussed above [9]. In Kolmogorov's 1941 theory the key parameter h, which is an exponent in the Navier-Stokes invariance scaling, is fixed at $h = 1/3$ but is allowed a spectrum of values in multifractal theory [10, 11, 12, 13]. Taking into account all derivatives of the Navier-Stokes equations, it is found that for this correspondence to hold the multifractal spectrum $C(h)$ (the co-dimension for a monofractal) must be bounded from below such that $C(h) \geq 1 - 3h$, a result which is consistent with the four-fifths law. Moreover, h must also be bounded from below such that $h \geq (1 - d)/3$. In 3 dimensions, the allowed range of h is given by $-2/3 \leq h \leq 1/3$ which is consistent with a range of fractal dimensions $D(h)$.

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HOW CLOSE ARE SHELL MODELS TO THE 3D NAVIER–STOKES EQUATIONS?

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Shell models have found wide application in the study of hydrodynamic turbulence because they are easily solved numerically even at very large Reynolds numbers [1–4]. Although bereft of spatial variation, they accurately reproduce the main statistical properties of fully-developed homogeneous and isotropic turbulence. Moreover, they enjoy regularity properties which still remain open for the three-dimensional Navier–Stokes equations [5–7]. The goal of this study is to make a rigorous comparison between shell models and the Navier–Stokes equations.

A mathematical description of the generation of small scales in turbulent 3D Navier–Stokes flows can be achieved by considering the L^{2m} norms of the velocity derivatives for weak solutions of the Navier–Stokes equations [8, 9]. Given a velocity field $\boldsymbol{u}$ over a periodic cube $\mathscr{V} = [0, L]^3$, scaling invariant volume integrals and norms can be defined as

$$F_{n,m} = \nu^{-1} L^{1/\alpha_{n,m}} \int_{\mathscr{V}} |\nabla^n \boldsymbol{u}|^{2m} \, \mathrm{d}V, \tag{1}$$

where ν is the kinematic viscosity and $\alpha_{n,m} = 2m/[2m(n+1) - 3]$. It was shown in [8, 9] that for $1 \leqslant n < \infty$ and $1 \leqslant m \leqslant \infty$, together with $n = 0$ for $3 < m \leqslant \infty$,

$$\langle F_{n,m}^{\alpha_{n,m}} \rangle_T \leqslant \; c_{n,m} \mathrm{Re}^3 + O\left(T^{-1}\right) \qquad \text{for Re} \gg 1, \tag{2}$$

where Re is the Reynolds number and $\langle\cdot\rangle_T$ denotes a time average up to time $T > 0$.

The shell-model counterpart of (1) is

$$F_{n,m} = \nu^{-1} k_f^{-n-1} \Big(\sum_{j=1}^{\infty} k_j^{2nm} |u_j|^{2m} \Big)^{\frac{1}{2m}}, \tag{3}$$

where k_f is the characteristic wave number of the forcing. The time average of $F_{n,m}$ is estimated in terms of Re and the result is compared with (2) [10].

It turns out that only the estimate of the mean energy dissipation rate ($n = m = 1$) is the same in both the 3D Navier–Stokes equations and shell models. The estimates of the velocity and its higher-order derivatives display a weaker Reynolds number dependence for shell models than for the 3D Navier–Stokes equations. Indeed, the velocity-derivative estimates for shell models are found to be equivalent to those corresponding to a velocity gradient averaged version of the 3D Navier–Stokes equations, in which $\|\nabla \boldsymbol{u}\|_\infty \approx c\, L^{-3/2} \|\nabla \boldsymbol{u}\|_2$. The velocity estimates are even milder.

Numerical simulations over a wide range of Reynolds numbers confirm the saturation of the estimates obtained for shell models.

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Tuesday 18 May 2021

Session 3

9:10 – 12:20

SIGNIFICANT THIN SHEAR LAYERS IN HIGH REYNOLDS NUMBER TURBULENCE

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Analyses and visualizations of the DNS data of high Reynolds number homogeneous isotropic turbulence (the Taylor micro-scale Reynolds number: $R_\lambda \sim 1000$) showed that there exist significant thin shear layers constructed by clusters of strong micro-scale vortices [1]. The size is of the order of the integral length scale and the thickness is of the order of the Taylor micro-scale. Within the layer, the averages of energy dissipation and energy transfer are approximately ten times larger than the mean value of the energy dissipation, and there exist extreme dissipation and enstrophy accompanied by velocity differences of the order of u' (the rms value of turbulent velocity fluctuations) [1,2]. Detailed visualization showed excellent correspondence between regions with high enstrophy values and the existence of strong shear layers[3].

A study of the temporal behavior of the strong shear layer in a time span of $10\tau_\eta = 2.55\lambda/u'$ (τ_η is the Kolmogorov time-scale and λ is the Taylor micro-scale) showed that strong vortices interact with the neighboring vortices and move drastically at a speed of the order of u', maintaining an effectively constant distance between each other; the average size of these peak vortices also remains quasi-time-independent; the strong shear layers at the interfacial region remain sharp during the time evolution [3]. The size of the order of the integral length-scale suggests that the layer is generated by large-scale eddy motions driven by forcing at large-scales. Visualization of the wider domain including the significant layer [4] showed that the layer is accompanied by a large-scale low-pressure vortex and is formed as a part of double spiral structure (Figure 1).

In this paper, the temporal behavior of the strong shear layer in a time span of $1.75T$ (T is the eddy-turnover time) is studied. The significant shear layer is observed to survive in visualizations of intense vorticity until at least $t = 60\tau_\eta$ from the time ($t = 0$) at which the layer was firstly identified. During this time, the average strength of the vortices inside the layer decrease slightly and then layer deformations are observed. After a while, another significant layer whose lifetime is of $O(T)$ is observed to appear under the correlated large-scale fluid motion. Note that, in the DNS, a negative viscosity was used for the Fourier modes at small-wavenumbers as the large-scale forcing, which is a deterministic forcing that enhances large-scale motions in turbulence keeping the total energy constant (see [5] for the details).

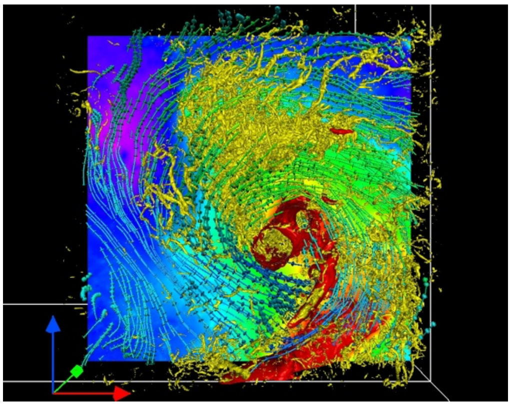

Figure 1. A significant thin shear layer as a cluster of strong micro vortices (shown in yellow) around low-pressure large-scale tubular vortex (shown in red). Streamlines are indicated by arrows. (From [4])

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COLLECTIVE VORTEX ORGANISATION IN TWO-DIMENSIONAL TURBULENCE

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Following the 'suggestion' from the unsupervised Monte–Carlo experiments in [1], that dipoles are as important to the dynamics of decaying two-dimensional turbulence, and as causally significant, as individual vortex cores, this talk summarises how far this suggestion can be developed to draw novel conclusions about the flow dynamics. For example, it was found in [2] that the kinetic energy of the flow is carried by elongated streams formed by the concatenation of dipoles (figure 1a). The coherent vortices of the flow separate into a family of small fast-moving cores, and another one of larger, slowly moving ones, that can be described as being'partially frozen' into a slowly evolving 'crystal'. The kinematics of the two families are very different. Both are self-similar, but follow different laws, and only the latter is responsible for most of the kinetic energy of the flow. Its vortices form the dipoles and streams whose creation embodies the inverse cascade of energy towards larger scales.
The talk also examines in which sense the slow component can be considered a 'crystal'. Several diagnostics of order are applied to the ostensibly disordered large vortices. It is shown that their geometric arrangement is substantially more regular than random (figure 1b), that they move more slowly than could be expected from simple mean-field arguments, and that their energy is significantly lower than a random reorganisation of the same vortices. This is traced to screening of long-range interactions by preferential association of vortices of opposite sign, and it is argued that this is due to the mutual capture of corrotating vortices, in a mechanism closer to tidal disruption than to electrostatic screening. Finally, the possible relation of these 'stochastic crystals' to fixed points of the turbulence system is briefly examined. Whether any of these conclusions extends to three-dimensional flows is unknown, but some of those issues are examined in other abstracts to this meeting.

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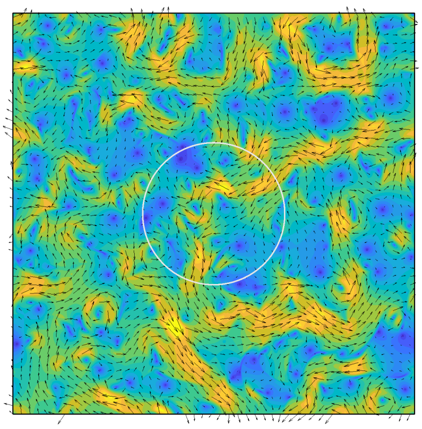
(a)



(b)

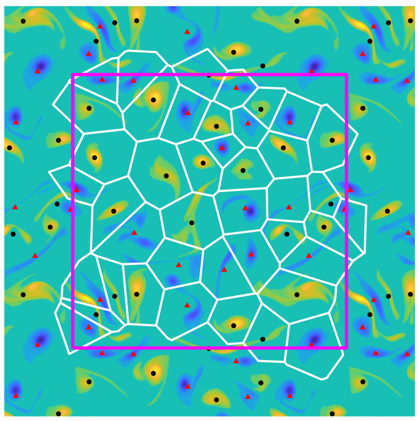


Figure 1. (a) Velocity field from a flow synthesised by retaining only vortices whose area is larger than the average. The background colour is the velocity magnitude, lighter for faster velocities. There are approximately 250 coherent vortices in the figure, and 60 large ones. (b) Voronoi tessellation of the point-vortex system formed by the centres of the large vortices in (a). The area distribution of the tessellae is approximately twice more concentrated than for a Poisson-distributed point set.

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Turbulent structure and intermittency in homogenous isotropic turbulence

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What kind of turbulent structures affect the flow most strongly? How do they do it? These questions have been discussed over the years, and still have no clear answers. To provide some of these answers, a large ensemble of three-dimensional direct numerical simulations of decaying homogenous isotropic turbulence are performed in a 64^3 grid, at Reynolds number $Re_\lambda \approx 50$. We define casually significant flow regions as those whose modification leads to a large change in the flow after some time, and our goal is to determine : first, whether such regions exist, and, second, whether they share some characteristic structure. To do this, 35 basic initial turbulent flows are first created, each of which is divided into 10^3 small cubes, 12η on the side. Next, the vorticity vector in each small cube is changed in four different ways (4 types of experiments), and the simulations are continued for one turnover time. The 'significance' of each experiment is defined after that time as the normalized L_2-norm of the velocity difference between the changed flow and the equivalent flow without modification, namely $\|\Delta \boldsymbol{u}\|/\|\boldsymbol{u}_i\|$, where $\Delta \boldsymbol{u}$ is the velocity difference and $\boldsymbol{u}_i$ is the velocity field of the initial flow. It measures the importance of the original sub-cube in determining the future behaviour of the flow as a whole. The process is repeated for each sub-cube and each type of experimental modification, for a total of $35\times1000\times4 = 1.4\times10^5$ simulations. This study follows a previous one in 2-D turbulence [1,2], presented in a different abstract to this workshop. Significant flow structures are found to correspond to cubes of strong enstrophy (see figure 1a). A 'template' for the structure of the flow within these significant cubes is obtained by aligning and averaging the top 1% most significant cubes, and is found to be a strong vortex in all cases. Furthermore, these significant parts are found to be related to the turbulent 'worms' (see figure 1b), which are well-known to be an intermittent part of the flow [3].

Funded by the Coturb ERC 2014.AdG-669505 grant.

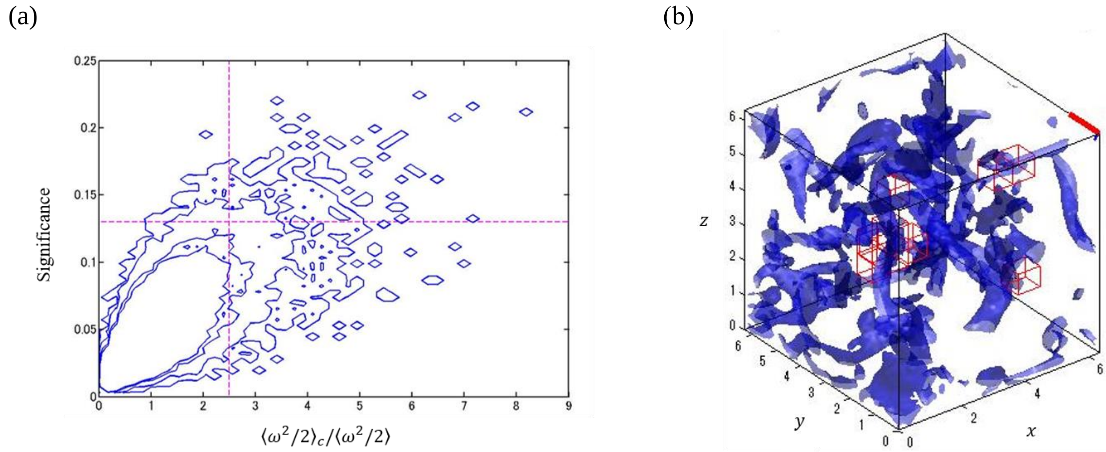

Figure 1. (a) Joint PDF of normalized enstrophy and significance for each box; $\langle\omega^2/2\rangle_c$ is the mean enstrophy in the box and $\langle\omega^2/2\rangle$ is the mean enstrophy in corresponding initial flow, the contour lines represent 0.8, 0.2, 0.1, and 0.01, respectively. The vertical and horizontal lines represent the threshold for detecting the strong vortex 'worms' and the top 1% most significant cubes, respectively. (b) 'Worms' detected by normalized enstrophy $\langle\omega^2/2\rangle_c/\langle\omega^2/2\rangle = 2.5$ of the background in the homogenous isotropic turbulence. The red boxes represent the 1% most significant parts of the flow.

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WHAT SCALES CONTROL THE EVOLUTION OF INTENSE EVENTS IN THE DISSIPATIVE RANGE OF ISOTROPIC TURBULENCE?

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Intermittency lies at the core of turbulent theory, but its origin remains unclear. The dissipation and the enstrophy are known to concentrate in regions of the flow where they become orders of magnitude larger than the mean. These intense events form structures whose origin and dynamics are not well understood, partly because of the strong non-linear and non-local nature of turbulence dynamics. Although intermittency has been widely regarded as a consequence of the energy cascade [1, 2], the velocity gradients are known to self-amplify through strictly local non-linear interactions [3], partially explaining intermittency without resorting to the cascade process. This leads to the question of whether intense events emerge due to a self-organisation process initiated in the dissipative range, or due to interactions at larger scales. In this talk we address this question by means of synchronisation experiments in direct numerical simulations of isotropic turbulence [4]. In these simulations, we apply a data assimilation procedure to show that, by imposing similar dynamics above the dissipative range to two independent turbulent flows, similar structures of intense vorticity are generated in the two flows, i.e intense vorticity synchronises to the dynamics of scales above the dissipative range (see figure). Remarkably, synchronisation happens despite the presence of chaotic dynamics (i.e. the synchronisation is only partial), and is more pronounced for the intense vorticity than for the weak vorticity background. We report that the dynamics at scales above 20η, where η is the Kolmogorov scale, largely control the magnitude and orientation of intense vorticity. For larger scales, synchronicity is progressively lost, but the orientation of the intense vorticity is still affected by scales up to 40η. These experiments show that the dynamics at the end of the inertial range are, to a large extent, a sufficient cause of the intense structures in the dissipative range, and that these structures are not primarily generated due to a self-organisation process, but due to large-scale dynamics. We propose that synchronisation is a consequence of the control exerted on the dissipative scales by the energy cascade process, which leads to the separation of the flow in cascade-driven regions of intense gradients, and in a weak and cascade-independent turbulent background. This separation emphasises the role of clusters of intense structures [5] in the energy cascade, and suggest that the synchronisation of intense gradients reflects the footprint of structures of inertial size – perhaps shear layers [6] – on the dissipative scales.

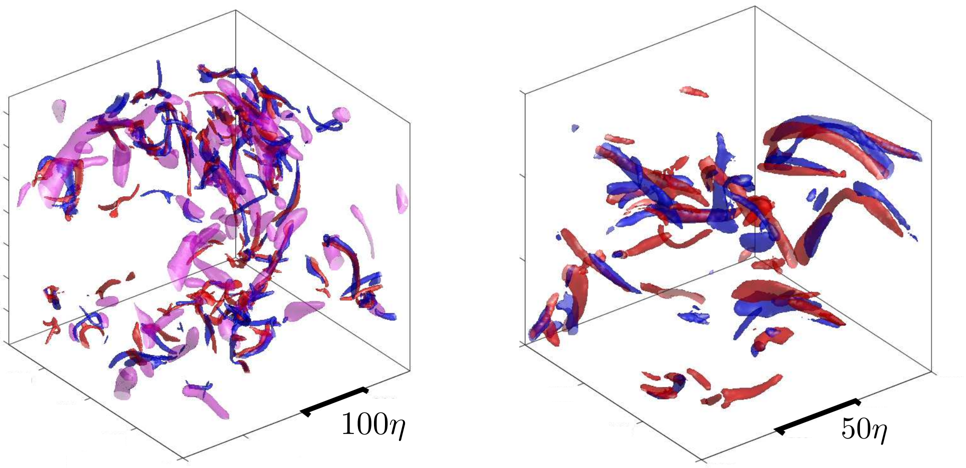

Figure 1. Visualisation of intense vorticity structures in two 'independent' flow fields (red and blue) with similar dynamics above $\ell = 20\eta$. The magenta isosurfaces mark intense vorticity at scales larger that ℓ, which are similar in the two fields due to an assimilation process. Conversely, the scales below ℓ evolve 'freely' under the Navier–Stokes equations. Note how similar structures of intense vorticity (red and blue) appear in the two flows.

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EXTREME DISSIPATION AT VERY HIGH REYNOLDS NUMBER

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The maximum dissipation rate in a turbulent flow is strongly Reynolds number dependent. Existing turbulence models and theories have proven inaccurate when predicting this Reynolds number dependence. In this talk we present a new model for the dissipation rate probability density function, which is based on the concept of significant shear layers. It is shown that this model accurately predicts the Reynolds number dependence of the maximum dissipation rate and the dissipation variance.

In our structural model, the turbulent flow is composed of large-scale background regions and layer regions. The volume fraction occupied by the latter scales according to Re_λ^{-1}, which is consistent with the layer thickness being proportional to the Taylor length scale [1,2]. Additionally, sublayers, and eventually sub-sublayers, develop at high Reynolds number. Furthermore, a uniform low-level background dissipation rate is defined, while the remaining dissipation is associated with the layer regions. The dissipation rates in these different regions are combined to produce the overall probability density function (PDF) of the dissipation rate. Subsequently, the maximum dissipation rate and the variance are determined from the PDF. The full model description is given in [3].

The dissipation maxima predicted by the present model are compared to those obtained from DNS of homogeneous isotropic turbulence (figure 1). At low Reynolds number ($Re_\lambda \sim 100$), the model and the DNS data yield a scaling exponent close to 1, which is, moreover, in agreement with observations in [4]. Furthermore, the present model reveals a gradual increase of the scaling exponent with the Reynolds number. A $\varepsilon_{max} \sim \langle\varepsilon\rangle Re_\lambda^{1.3}$ scaling is obtained in the range $Re_\lambda \approx 400$ – 1100, which is again consistent with our data and those of [5]. Note that the scaling predicted by multifractal theories [6], i.e. $\varepsilon_{max} \sim \langle\varepsilon\rangle Re_\lambda^{2}$, is not observed in the data. Finally, we comment that the gradually increasing scaling exponent has significant implications for flows at very high Reynolds numbers, such as occurring in the atmosphere and astrophysics.

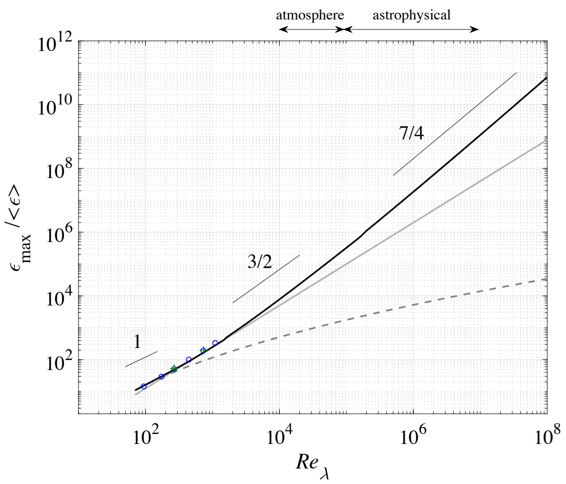

Figure 1. Maximum dissipation rate, ε_{max}, versus Reynolds number as predicted by the present model (black line). Blue (o) and green (+) symbols indicate the maximum dissipation rate obtained from DNS data of homogenous isotropic turbulence at resolution $k_{\max}\eta$ = 2 and 4 respectively. The grey solid line shows a constant power law with exponent 1.3, while the gray dashed line is for a lognormal distribution of the dissipation rate.

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HELICAL TRIAD PHASE COHERENCE IN 3D NAVIER-STOKES TURBULENCE

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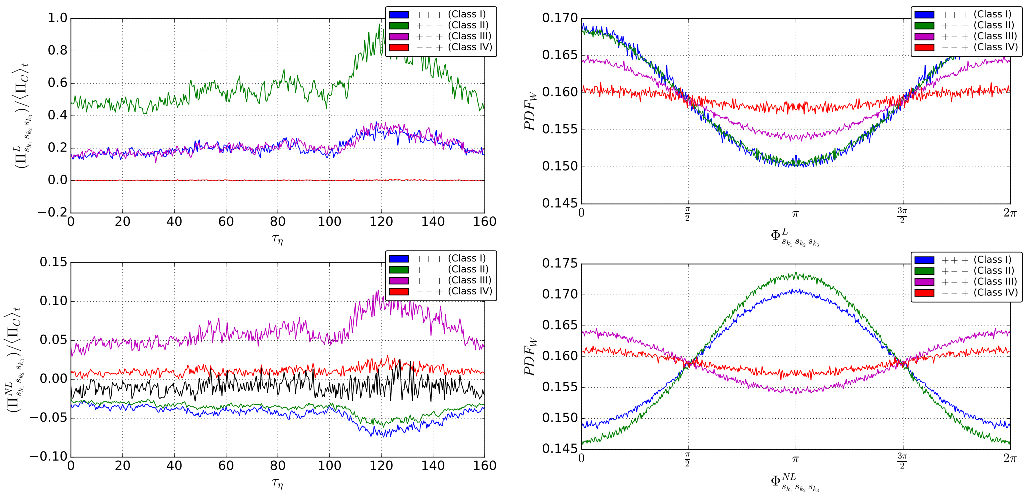
We study the role of the coherence of the helical [3] triad phases on the spectral flux of energy towards small scales in 3D Navier-Stokes direct-cascade turbulence, by performing numerical simulations at resolution 512^3 with a Reynolds number $Re \equiv ((2\pi/k_f)/\eta)^2 \approx 28074$ in terms of the Kolmogorov length scale $\eta \approx 0.025$ and a large-scale $(0.5 \leq k_f \leq 1.5)$ Ornstein-Uhlenbeck time-correlated stochastic forcing [2, 1]. We first demonstrate a flux formula for the nonlinear energy flux from the inertial range $1.5 \leq |\mathbf{k}| \leq K_C := 15$ towards the dissipation range $K_C < |\mathbf{k}| < 170$ (where flux and dissipation are comparable) in terms of the helical triad phases $\Phi^{s_1 s_2 s_3}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3}$, helical amplitudes $a^s_{\mathbf{k}}$ and helical vectors $\mathbf{h}^s_{\mathbf{k}}$,

$$\begin{aligned} 2\Pi_C \;=\; & \sum_{|\mathbf{k}_1|,|\mathbf{k}_2|\leq K_C<|\mathbf{k}_3|,\quad \mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3=0,\quad s_1,s_2,s_3\in\{\pm\}} \left|(s_2k_2 - s_1k_1)[\mathbf{h}^{s_1}_{\mathbf{k}_1}\times\mathbf{h}^{s_2}_{\mathbf{k}_2}\cdot\mathbf{h}^{s_3}_{\mathbf{k}_3}]\right| a^{s_1}_{\mathbf{k}_1}a^{s_2}_{\mathbf{k}_2}a^{s_3}_{\mathbf{k}_3}\cos(\Phi^{s_1s_2s_3}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3}) \\ + & \sum_{|\mathbf{k}_1|\leq K_C<|\mathbf{k}_2|,|\mathbf{k}_3|,\quad \mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3=0,\quad s_1,s_2,s_3\in\{\pm\}} \left|(s_2k_2 - s_3k_3)[\mathbf{h}^{s_1}_{\mathbf{k}_1}\times\mathbf{h}^{s_2}_{\mathbf{k}_2}\cdot\mathbf{h}^{s_3}_{\mathbf{k}_3}]\right| a^{s_1}_{\mathbf{k}_1}a^{s_2}_{\mathbf{k}_2}a^{s_3}_{\mathbf{k}_3}\cos(\Phi^{s_1s_2s_3}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3})\,. \end{aligned} \tag{1}$$

Second, with a Kolmogorov time microscale of $\tau_\eta \approx 0.25$, helical triad-phase flux-weighted PDFs were computed over a simulation runtime of $\approx 240\,\tau_\eta$. We observe an imbalance between positive and negative contributions to the flux, leading to peaks in the flux-weighted PDFs for the helical triad phases $\Phi^{s_1s_2s_3}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3}$: peaks at $\Phi = 0$ indicate a positive forward cascade while peaks at $\Phi = \pm\pi$ indicate an inverse flux. In the figure below, the left panels show the time evolution of the relative flux contribution $\Pi^{s_1s_2s_3}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3}$ for the four independent generalised helical triad phase types to the energy flux as described in the flux formula (1). The top panels correspond to *local* helical triads, namely those contributing to the first term in the flux formula (1), amounting to only 0.3% of the total triad interactions, but contributing to over 90% of the total flux: the left panel shows the flux contributions and the right panel shows the flux-weighted PDF of *local* helical triads. The bottom panels show the *non-local* helical triad contributions, namely those contributing to the second term in the flux formula (1): the left panel shows the flux contributions (black line indicates the cumulative flux for these non-local triad types) and the right panel shows the flux-weighted PDF of *non-local* helical triads. These observations are in agreement with the usual paradigm stemming from Waleffe's triad coefficient analysis.



Along with a Kuramoto-parameter synchronisation analysis (not shown), the above results provide evidence for the role of helical triad phase dynamics in the energy flux between large and small scales; there is a rich behaviour depending on the locality of the wavevectors forming a triad, with clear evidence that for *non-local* triads of Class I and II we have a well developed and coherent inverse cascade over a large number of triads. This effect is hidden when simply looking at the classical fluxes, because of the diminished size of the helical amplitudes multiplying the static interaction coefficients.

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Tuesday 18 May 2021

Session 4

14:00 – 17:10

STUDYING OF INTERMITTENCY AND BURSTING PHENOMENA IN STRATIFIED BOUNDARY LAYER USING PROBABILITY DENSITY FUNCTIONS

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We processed datasets of fine-scale measurements of nocturnal turbulence in the Atmospheric Boundary Layer (ABL) taken by a sonic- and hot-film anemometer dyad during the field campaigns of MATERHORN Program to identify burst (anomalously high periods of turbulent kinetic energy dissipation) and no-burst events, and the two datasets were analyzed separately. Additionally, we conducted Direct Numerical Simulations (DNS) in a box at four different grid resolutions, yielding datasets of Homogeneous and approximately Isotropic Turbulence (HIT) at four Reynolds numbers. The structure functions of higher order p varying from 1 to 6 were carefully investigated to lit light on the anisotropy effects caused by stratification typical for nocturnal turbulence and a submitted manuscript is under consideration. In the current study, the analysis was focused on Probability Density Functions (PDFs), allowing to assess the effects of bursting by studying the variations of shapes of 3rd moment for longitudinal velocity derivative $\partial_x u$ based on canonical normalization using 2nd order moment (skewness) and new type of normalization (modified skewness) using 3rd moment of modulus of velocity derivative $\left|\partial_x u\right|$ as suggested in Sukoriansky et al. [1]. All PDF computations indicate non-Gaussian wide tails for high values of dimensionless velocity increments and derivatives, which may be associated with internal intermittency of turbulent flows. The shapes of PDFs in field experiments for no-burst and burst periods differ significantly. For "no-burst" dataset, the shape at origin resembles that of the normal PDF while for the "burst" dataset a "cusp" was evident and PDF at $\partial_x u = 0$ is significantly higher. General shapes of PDFs evaluated for longitudinal velocity derivatives in nocturnal turbulence are more symmetrical than those obtained in DNS carried out in the current study representing approximately homogeneous isotropic turbulence. Similarly, more symmetrical shapes were observed in direct numerical simulations of stably stratified shear flows. The results allow to conclude that symmetry of PDF of longitudinal velocity derivative of velocity components is not determined by the isotropy of turbulence.

MOLECULES, MAGNETIC FIELDS AND INTERMITTENCY IN COSMIC TURBULENCE: FOLLOWING THE ENERGY TRAIL

Edith Falgarone[1], Thibaud Richard[1], Pierre Hily-Blant[2], Alba Vidal-Garcia[1], Pierre Lesaffre[1], Benjamin Godard[1], Andrew Lehmann[1], Guillaume Pineau des Forêts[1]
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Gravity drives the evolution of the universe, but the gas dissipative dynamics is a central, yet unsolved, issue in the theory of galaxy formation. Turbulence being ubiquitous in the diffuse material out of which stars and galaxies form, turbulent dissipation is among the most critical dissipative processes along galaxy evolution. Cosmic turbulence is highly compressible, multi-phasic and magnetised with huge Prandtl numbers. It encompasses at least 10 orders of magnitude in scales making it out-of-reach of brute-force numerical simulations.
It is chemistry that is providing us with an unexpected clue. Alike photo-luminescent plankton that shines in the strong velocity shears in the breaking waves of tropical oceans, a handful of molecules have such large formation enthalpies that they highlight the dissipation bursts of turbulence.
Our team therefore progresses along several complementary directions:
- models of out-of-equilibrium chemistry in intermittent turbulent dissipation regions [1],
- confrontation of these models to observations in the high-redshift universe [2, 3],
- numerical simulations of compressible magneto-hydrodynamical turbulence dedicated to dissipation processes [4],
- observations of the small-scale gas dynamics in nearby interstellar matter [5, 6].
Each of these approaches have limitations, but they have led to breakthroughs and many new questions. This abstract refers to the first and second ones. Attempts to model the outcome of ion-neutral chemistry in magnetized Burgers vortices will be presented, illustrated by a selection of observational results and their scope.

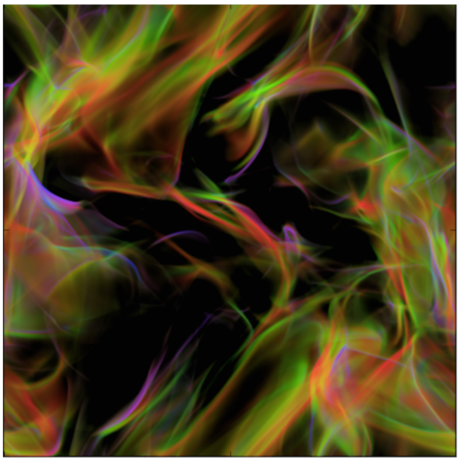

Figure 1. Extrema of dissipation in a 1020^3 cube of compressible magnetised turbulence (sonic Mach number = 4) with dissipation due to solenoidal viscosity (green), compressive viscosity (blue) and resistivity (red) [4]. All these dissipation processes are entangled. These simulations are dimensionless but scaled to a diffuse gas density of 100 cm^{-3}, and an Alfvén velocity $v_{\mathrm{A}} = 2.8$ km s^{-1} for $B = 10\mu$G, the resolution is $\sim$ 1 mpc (or 3$\times$ 10^{15} cm), the box size is $\sim$ 1 pc and the thickness of the smallest dissipative structures $\sim$10 mpc.

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COHERENCE OF EXTREME DISSIPATION STRUCTURES IN A NON-STAR-FORMING MOLECULAR CLOUD

Pierre Hily-Blant[1], Edith Falgarone[2], Simon Delcamp[1], and the MIST team
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Stars form in turbulent molecular clouds as the outcome of a complex opposition between gravity and the gas dissipative dynamics. Turbulence in molecular clouds is highly compressible and magnetized, so that the characteristics of turbulent dissipation—its rate, its spatial distribution, its impact on the gas micro-physics—are an uncharted territory.

We have selected a nearby molecular clouds in which gas motions are primarily turbulent. Using one-dimensional velocimetry experiments based on the Doppler-shift of molecular lines observed at very high spectral resolution, we have performed a map of the increments of line centroid velocity (projected along the line of sight) from which both the structures and statistics of intermittency could be derived. Multi-scale observations show the coherence of the velocity field over more than three orders of magnitude in spatial scale; this coherence appears as straight edges of structures, the orientation of which is strikingly preserved from the largest down to the smallest scales probed, still two orders of magnitude above the molecular mean-free path. Combining various tracers, the physical conditions, including the temperature, in the gas indicate extreme variations below the resolved scales. Altogether, these data point towards a region of extreme dissipation, offering unique opportunities to characterize the structures responsible for it, and constrain the rate at which kinetic energy is irreversibly turned into heat[1].

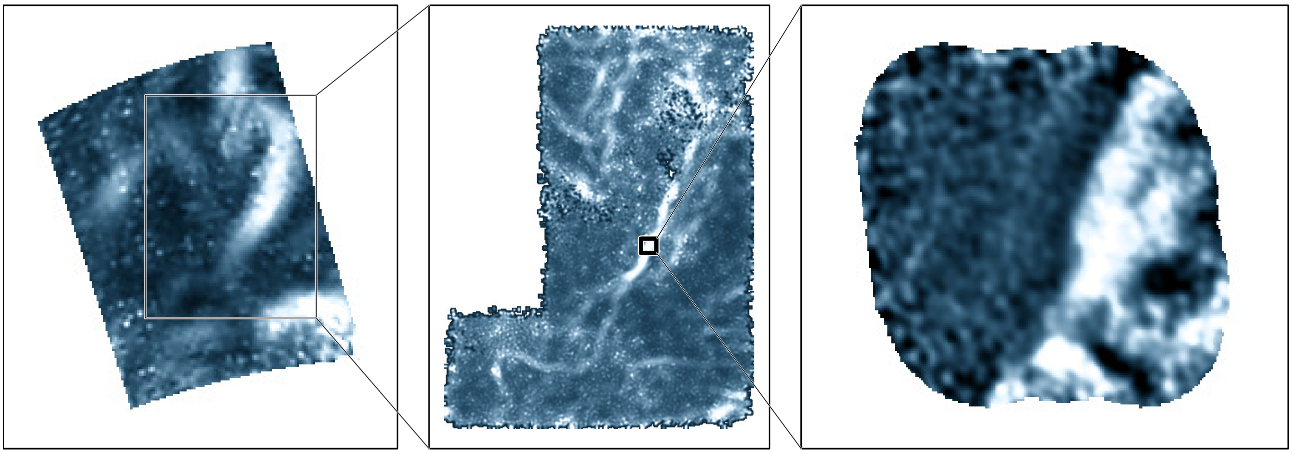

Figure 1. Maps of the line centroid velocity increments (CVI) toward the Polaris molecular cloud, as seen with increasing spatial resolution (x10 from each panel to the next). The intense CVI (white regions) appear as straight structures showing spatial coherence from large to small scales, from coarse to fine resolution. At the finest resolution, large-increments structures are straight edges that preserve the orientation of the embedding, larger CVI structures. The structures seen in the right panel are envisioned as embedding structures of extreme dissipation that are observable at a x10 better resolution with the James Webb Space Telescope.

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RECONNECTION-CONTROLLED DECAY OF MAGNETOHYDRODYNAMIC TURBULENCE AND THE ROLE OF INVARIANTS

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We present a new theoretical picture of magnetically dominated, decaying turbulence in the absence of a mean magnetic field. With direct numerical simulations, we demonstrate that the rate of turbulent decay is governed by the reconnection of magnetic structures, and not necessarily by ideal dynamics, as has previously been assumed. We obtain predictions for the magnetic-energy decay laws by proposing that turbulence decays on reconnection timescales, while respecting the conservation of certain integral invariants representing topological constraints satisfied by the reconnecting magnetic field. As is well known, the magnetic helicity is such an invariant for initially helical field configurations, but does not constrain non-helical decay, where the volume-averaged magnetic-helicity density vanishes. For such a decay, we propose a new integral invariant, analogous to the Loitsyansky and Saffman invariants of hydrodynamic turbulence, that expresses the conservation of the random (scaling as $\mathrm{volume}^{1/2}$) magnetic helicity contained in any sufficiently large volume. We verify that this invariant is indeed well-conserved in our numerical simulations. Our treatment leads to novel predictions for the magnetic-energy decay laws: in particular, while we expect the canonical $t^{-2/3}$ power law for helical turbulence when reconnection is fast (i.e., plasmoid-dominated or stochastic), we find a shallower $t^{-4/7}$ decay in the slow 'Sweet-Parker' reconnection regime, in better agreement with existing numerical simulations. For non-helical fields, for which there currently exists no definitive theory, we predict power laws of $t^{-10/9}$ and $t^{-20/17}$ in the fast- and slow-reconnection regimes, respectively. We formulate a general principle of decay of turbulent systems subject to conservation of Saffman-like invariants, and propose how it may be applied to MHD turbulence with a strong mean magnetic field and to isotropic MHD turbulence with initial equipartition between the magnetic and kinetic energies.

PROBING THE NATURE OF DISSIPATION EXTREMA IN COMPRESSIBLE MHD TURBULENCE

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Observations of specific molecular tracers in the cold diffuse interstellar medium (ISM) require intense local energy injection without the need of compression. Sometimes the observed tracers are known to originate from chemical routes subject to large temperature thresholds (Godard et al. 2014, Lesaffre et al. 2013). Most of the proposed channels to explain these molecular observations are related to specific localized structures where turbulent dissipation is enhanced. In the present study, we choose to probe the turbulent dissipation with grid based simulations of compressible isothermal decaying MHD turbulence, that take unprecedented care at resolving and controlling dissipation.
Strong dissipation is necessarily associated with strong variations of the state variables of the gas. We designed a way to assess locally the main direction of the gradients of the physical state of the gas. We observe that the regions of strongest dissipation have their gradients mainly along one direction, and study in detail the variation of fluid variables in this direction (figure 1). We use a combination of heuristic criteria (on the profiles of state variables) and the decomposition of gradients into a basis of MHD waves to identify the nature of the processes that cause these structures to appear. With this new method we identified four categories of structures responsible for the strongest bursts of dissipation. Two of them are shocks: slow shocks and fast shocks. The other two are Alfvén discontinuities (the gas enters in the dissipative layer of the discontinuity at Alfvén velocity): rotational discontinuities and what we have called Parker sheets.
These four types of discontinuities comprise the majority of the high dissipation structures we find in our simulations. We are therefore able to assign the dissipation of large-scale flows to the different types of structure and we examine their statistical properties. In particular, we find that even in this highly compressible situation, dissipation is mainly caused by weakly compressive structures (Alfvén discontinuities).

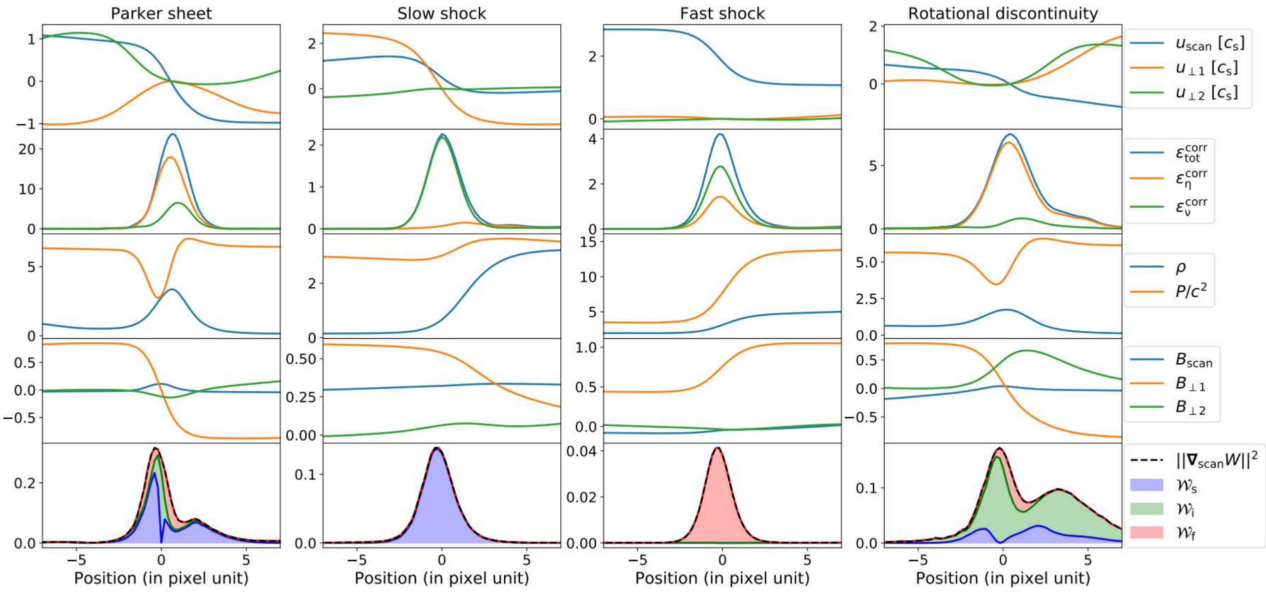

Figure 1: Scan profiles used to identify the different kinds of dissipation structures in our simulations. The four first lines of plots show respectively velocity, dissipation rates (total, ohmic and viscous), density and total pressure, magnetic field profiles. The last shows gradients decomposition in pure waves. The colored part under each curve gives the weight of each corresponding pure wave.

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INTERMITTENCY OF VELOCITY CIRCULATION IN QUANTUM AND CLASSICAL TURBULENCE

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The velocity circulation, a measure of the rotation of a fluid within a closed path, is a fundamental observable in classical and quantum flows. It is indeed a Lagrangian invariant in inviscid classical fluids. In quantum flows, circulation is quantized, taking discrete values that are directly related to the number and the orientation of thin vortex filaments enclosed by the path. By varying the size of such closed loops, the circulation provides a measure of the dependence of the flow structure on the considered scale. Recently, high Reynolds number simulations have shown evidence of a very simple structure of the circulation moments due to intermittency [1]. Concretely, circulation moments are accurately described by a bifractal model, which contrasts with the more complex multifractal description of velocity increment statistics resulting from intermittency.

In this talk, I will present some recent results for the circulation statistics in (superfluid) quantum turbulent flows [2]. One of the most striking properties of superfluids is the existence of *quantum vortices*, topological defects where the macroscopic wave function describing the system vanishes. In three-dimensional space, quantum vortices take the form of thin filaments. Moreover, the velocity circulation about such vortices is quantized in units of the quantum of circulation $\kappa = h/m$, where h is Planck's constant, and m is the mass of the bosons constituting the superfluid. Quantum turbulence is characterized by different scaling ranges. At scales much larger than the mean inter-vortex distance, the quantum nature of vortices can be ignored and the Kolmogorov phenomenology dictates the energy transfer. On the contrary, at scales smaller than the inter-vortex distance, energy transfers are driven by the dynamics of Kelvin waves and vortex reconnections.

We produced numerically a quantum turbulent flow using high-resolution direct numerical simulations of a generalized Gross–Pitaevskii model. Using these simulations, we compared the circulation statistics obtained in quantum turbulence, to simulations of the incompressible Navier–Stokes equations. When the integration path, where circulation is computed, is smaller than the mean inter-vortex distance, the statistics of circulation in quantum turbulence display an extreme intermittent behavior due to the quantization of circulation, in stark contrast with the viscous scales of classical flows. In contrast, at larger scales, circulation moments display striking similarities with the statistics probed in the inertial range of classical turbulence. This includes the emergence of the power-law scalings predicted from Kolmogorov's 1941 theory, as well as intermittency deviations that closely follow the recently proposed bifractal model for circulation moments in classical flows. To date, this is the most convincing evidence of intermittency in the large scales of quantum turbulence.

Moreover, our results strongly reinforce the resemblance between classical and quantum turbulence, highlighting the universality of inertial range dynamics, including intermittency, across these two a priori very different systems. This work paves the way for an interpretation of inertial range dynamics in terms of the polarization and spatial arrangement of vortex filaments.

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Wednesday 19 May 2021

Session 5

9:10 – 12:20

Experimental and numerical investigations around the 4th Millenium problem (Navier-Stokes existence and smoothness)

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Incompressible fluids are described by the Navier-Stokes equations. Yet, it is not yet known whether the Cauchy problem is well posed for these equations, and whether solutions of finite energy are regular or unique.

From a practical point of view, two interesting questions arise: if there is a blow-up solution, what is his shape? Is there a loss of unicity after the blow-up?

This talk describes experimental and numerical investigations that are devised to provide helpful intuitions regarding these two questions. In particular, I will show how to detect and characterize areas of “lesser regularity” and how to connect them with possible intermittency and loss of unicity.

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LAGRANGIAN IRREVERSIBILITY AND INTERMITTENT DISSIPATION IN TURBULENCE

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Turbulent flows are both irreversible and intermittent; they dissipate energy in an extremely non-uniform manner with sheet-like intense zones punctuating an otherwise moderate dissipation field (Fig. 1a). This spatial manifestation of intermittency may be juxtaposed with the Lagrangian signature of irreversibility, namely the "flight-crash" events experienced by fluid particles (tracers) whose kinetic energy fluctuations are dominated by gradual gains and sudden losses [1]. Imagining these fluid particles navigating the intermittent dissipation field, one naturally wonders whether the two phenomena are linked: Do fluid particles slowly build up energy in the vast regions of mild dissipation only to crash when they eventually encounter regions of intense dissipation?

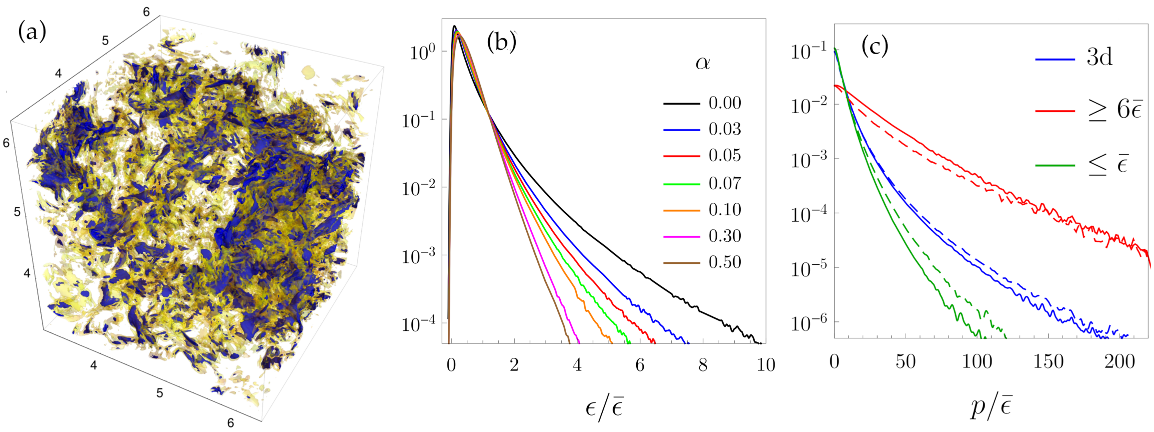

Figure 1. (a) Contours of intense Eulerian energy dissipation ($\varepsilon = 6\bar{\varepsilon}$ in blue and $\varepsilon = 4\bar{\varepsilon}$, in yellow); (b) pdfs of ε in flows with an increasing fraction α of decimated fourier modes; (c) pdf of power p in zones of intense (red) and mild (green) dissipation, as well as in the full domain (blue), of a non-decimated, intermittent turbulent flow. The negative tail is reflected and shown as a dotted line. Here, a negative skewness indicates flight-crashes while a positive skewness points to take-off events.

We address this question via direct numerical simulations of intermittent, as well as non-intermittent turbulent flows. The latter are obtained by solving the Fourier-decimated Navier-Stokes equations. Increasing the fraction of suppressed Fourier modes results in a loss of extreme dissipation events, and the corresponding probability distribution function (pdf) transitions from its typical wide-tailed, log-normal profile to a narrow exponential distribution (Fig. 1b). On comparing the power-fluctuations of tracers transported by an intermittent and a decimated flow, we find a surprising result: the flight-crash signature is *enhanced* in decimated flows that are devoid of intense dissipation zones. Indeed, rather than crashing, fluid particles that encounter intense dissipation zones actually gain energy rapidly and *take-off* (Fig. 1c). Using conditioned-statistics along with theoretical arguments, we show that this unexpected behaviour is due to the work done by the pressure-gradient, which accelerates particles out of these zones of intense dissipation [2]. Our work thus reveals the connection between Lagrangian irreversibility and Eulerian dissipation, while highlighting the usefulness of decimated turbulent flows for investigating the impact of intermittency and extreme dissipation events on the turbulent transport of particles and scalars.

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EXPLORATION OF LAGRANGIAN AND EULERIAN IRREVERSIBILITY IN AN EXPERIMENTAL VON KÁRMÁN FLOW

Cheminet Adam[1], Debue Paul[1], Valori Valentina[1], Ostovan Yasar[2], Cuvier Christophe[2], Laval Jean-Philippe[2], Foucaut Jean-Marc[2], Daviaud François[1] & Dubrulle Bérengère[1]
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[2] *Univ. Lille, CNRS, ONERA, Arts et Métiers ParisTech, Centrale Lille, FRE 2017-LMFL-Laboratoire de Mécanique des Fluides de Lille-Kampé de Fériet, F-59000, Lille, France*

In a turbulent fluid, the time-reversal symmetry is explicitly broken by viscosity, and spontaneously broken in the inviscid limit [Onsager, 1949, Frisch, 1995, Jucha et al., 2014]. To understand the physical origin of this mechanism, one needs to define an equivalent of the order parameter that allows to trace the time irreversibility locally in space and time. Recently, two different local indicators of time-irreversibility have been suggested : an Eulerian one, based on regularity properties of the velocity field [Duchon and Robert, 1999] ; and a Lagrangian one, based on symmetry properties of the trajectories under time reversal [Drivas, 2019].

A proof that the two indicators are equivalent was given in [Drivas, 2019]. Under certain hypotheses such as $\nu \to 0$ and $\ell \to 0$, the local scale at which turbulence is probed, both indicators are equal to the local dissipation $\epsilon(x,t)$.

In this talk, I will test the equivalence of the two indicators in a turbulent Von Kármán experiment in our facility at CEA. The flow is generated by two counter-rotating impellers fitted with blades. Thanks to a high resolution 4D-PTV technique [Ostovan et al., 2019], we obtain time-resolved Lagrangian trajectories (see Fig. 1(a)). The Eulerian velocity field is obtained by regularized B-spline interpolation with a resolution of the order of the Kolmogorov scale. We use these measurements to compare Eulerian (see Fig. 1(b)) and Lagrangian signatures of irreversibility and link them with peculiar properties of the local velocity field and particle trajectories. We will especially focus on describing the behaviors of particle trajectories in and around events of high negative or positive irreversibility. We will investigate how those events impact single particle statistics as well as particle dispersion statistics and link them with dissipative eulerian structures.

Finally, I will introduce a new experimental facility that is now build at CEA, a Giant Von Kármán, which will allow us to probe the turbulence well bellow the Kolmogorov scale where we hope to unveil singular events of strong dissipative nature [Dubrulle, 2019].

a) b)

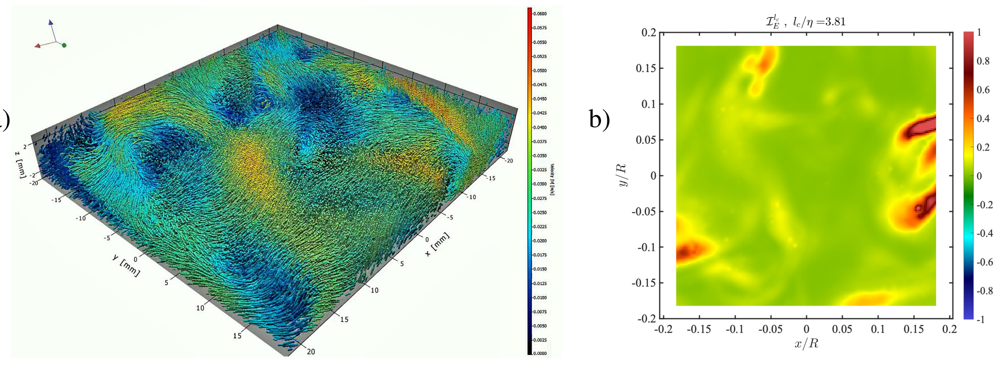

Figure 1. (a) An example of velocity color coded Lagrangian trajectories obtained in the DNS at $Re_\lambda = 62$. (b) Snapshot of the Eulerian Irreversibility indicator at the center of our measurement volume.

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IDENTIFICATION OF TURBULENT STRCUTURE IN PIPE FLOW USING TOMOGRAPHIC PIV

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Implementation of visualization techniques is carried out that aim at the interpretation of the complex turbulent structures in fluid flow. Turbulent structures in flow represent important phenomena like rotation, shearing, stretching, and compression and can provide insight in various phenomena of the flow field such as energy dissipation and drag mechanism. The studies for the visualization of turbulent structures are majorly on the vortex tubes and few studies are found regarding vortex sheet structure identification for experimental data. Using the Tomographic PIV method, experimental data for the three-dimensional instantaneous velocity vector field was measured for pipe flow. Q criterion analysis [1] was employed for visualization of vortex tubes in a time series flow field measurement. Vortex sheets were visualized using the Aij matrix analysis [2] that utilizes second-order velocity gradient tensor and its eigenvalues for identifying regions with a high correlation and magnitude of vorticity and strain. The relative position of the tube and sheet structures visualized and compared with structures of DNS data for pipe flow. Instantaneous visualization of these structures with regions of high energy dissipation was also visualized.

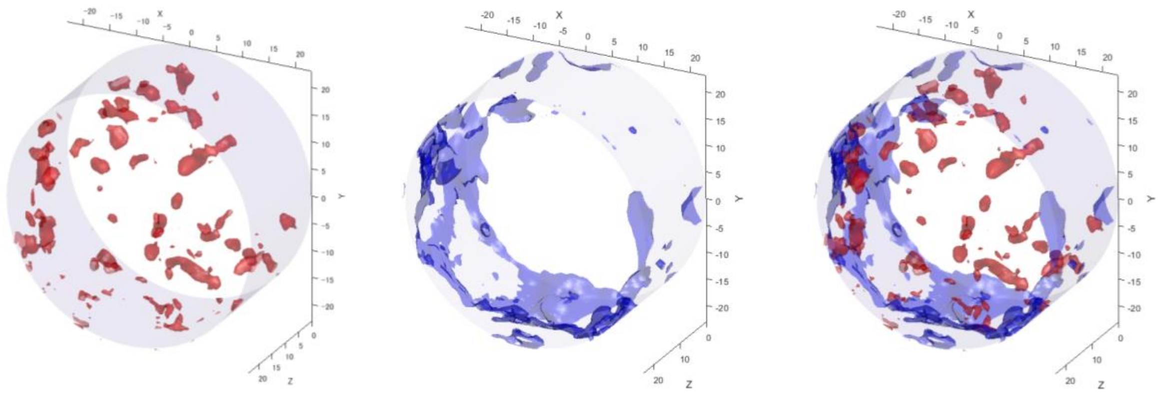

Figure 1. Vortex tubes (left) and sheet (center) structure representation in the pipe flow at Re=25000 using Q criterion and Aij analysis. Right image shows the combined tubes and sheet structures.

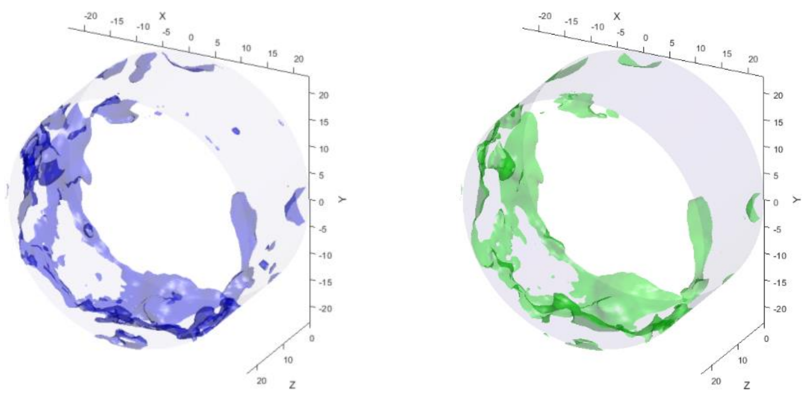

Figure 2. Vortex sheet structure (left) representation along with high energy dissipation region (right) in the pipe flow at Re=25000.

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TIME-REVERSIBLE NAVIER-STOKES EQUATIONS

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We present a comprehensive study of the statistical features of a three-dimensional time-reversible Navier-Stokes (RNS) system, wherein the standard viscosity ν is replaced by a fluctuating thermostat that dynamically compensates for fluctuations in the total energy. We analyze the statistical features of the RNS steady states in terms of a non-negative dimensionless control parameter $\mathcal{R}_{\rm r}$, which quantifies the balance between the fluctuations of kinetic energy at the forcing length scale $\ell_{\rm f}$ and the total energy E_0. For small $\mathcal{R}_{\rm r}$, the RNS equations are found to produce "warm" stationary statistics, *e.g.* characterized by the partial thermalization of the small length-scales. For large $\mathcal{R}_{\rm r}$, the stationary solutions have features akin to standard hydrodynamic ones: They have compact energy support in k-space and are essentially insensitive to the truncation scale $k_{\max}$. The transition between the two statistical regimes is observed to be smooth but rather sharp. Using insights from a diffusion model of turbulence (Leith model), we argue that the transition is in fact akin to a *continuous phase transition*, where $\mathcal{R}_{\rm r}$ indeed behaves as a thermodynamic control parameter, *e.g.* a temperature. A relevant order-parameter can be suitably defined in terms of a (normalized) enstrophy, while the symmetry breaking parameter h is identified as (one over) the truncation scale $k_{\max}$. We find that the signatures of the phase transition close to the critical point $\mathcal{R}_{\rm r}^\star$ can essentially be deduced from a heuristic mean-field Landau free energy. This point of view allows us to reinterpret the relevant asymptotics in which the *dynamical ensemble equivalence* conjectured by Gallavotti, *Phys.Lett.A, 223, 1996* could hold true. We argue that Gallavotti's limit is precisely the joint limit $\mathcal{R}_{\rm r} \overset{>}{\to} \mathcal{R}_{\rm r}^\star$ and $h \overset{>}{\to} 0$, with the overset symbol ">" indicating that these limits are approached from above. The limit therefore relates to the statistical features at the critical point. In this regime, our numerics indicate that the low-order statistics of the 3D RNS are indeed qualitatively similar to those observed in direct numerical simulations of the standard Navier-Stokes (NS) equations with viscosity chosen so as to match the average value of the reversible viscosity. This result suggests that Gallavotti's *equivalence conjecture* could indeed be of relevance to model 3D turbulent statistics, and provides a clear guideline for further numerical investigations at higher resolutions [1].

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FINITE DISSIPATION FROM HELICITY FOLLOWING RECONNECTION

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A seemingly never ending issue in our understanding of fundamental turbulence is that the parameterisations used by large-eddy simulations inherently assume that the turbulent rate of dissipation of the kinetic energy is finite. Despite one type of mathematics in $\mathbb{R}^3$, that is infinite whole space, that suggests that a finite dissipation rate, $\epsilon = \nu Z$, $Z = \|\omega\|_2^2$ and ω vorticity, cannot be maintained unless the underlying equations have singularities. And for $\nu \equiv 0$ Euler solutions far from boundaries, the strongest numerical growth is only doubly-exponential, not singular [1], which is now supported by analysis of Taylor-Green-Euler data. Many direct simulations have attempted to resolve these issues.

When simulating interacting vortices, among the successes are simulations that when run long enough at high enough Reynolds number, turbulent statistics and spectra will develop [2], including vorticity moments that obey a new hierarchy found for homogeneous, isotropic turbulence [3], a hierarchy that also underlies the recent Euler conclusions [1]. However, a more desireable set of calculations would be ones that generate and maintain finite ϵ by a Reynolds number independent time, preferably a time closer to the end of the first reconnection at t_x. Existing calculations do not do this well.

My new calculations are extensions in time and Reynolds numbers of the calculations in [4], a strongly perturbed trefoil vortex knot and very long, perturbed anti-parallel vortices and the goal is to extend those calculations into a regime with both convergent ϵ as ν decreases and a $k^{-5/3}$ inertial range spectrum at $t_\epsilon \approx 2t_x$.

A common feature of both sets of calculations is that they are done in very large periodic domains, with the domain size increasing as the viscosity ν decreases. The reasons given [4] are based upon the mathematics of Constantin (1986), mathematics that can also help explain why symmetric initial states can never provide the answers. To accommodate the large domains, the vortices of the anti-parallel set are very long with a localised perturbation. For the trefoil knots, the initial helical vortex state is confined within small volume, so it is mathematically compact.

Besides tracking the convergence of $\epsilon(t)$ as $\nu \to 0$ and spectra, the exchange of circulation convergence in the early reconnection phase is improved and there is new helicity analysis using the helicity flux along vortex tubes and spectra. The figures below are from an extension of the $\nu = 7.8 \times 10^{-6}$, $Re = \Gamma/\nu = 64,000$ trefoil with $t_x \approx 41$ [4]. During the trefoil's reconnection phase the global helicity barely changes, but both the physical and Fourier space analysis shows negative helicity being transported to small scales, which is compensated for by positive helicity moving to large scales. Then, during viscous reconnection, most of small-scale negative helicity is dissipated. Leaving behind an global increase in the positive helicity. The strong perturbation is essential for achieving these results, as three-fold symmetric trefoils suppress ϵ growth much as close, periodic boundaries can suppress such growth for anti-parallel vortices.

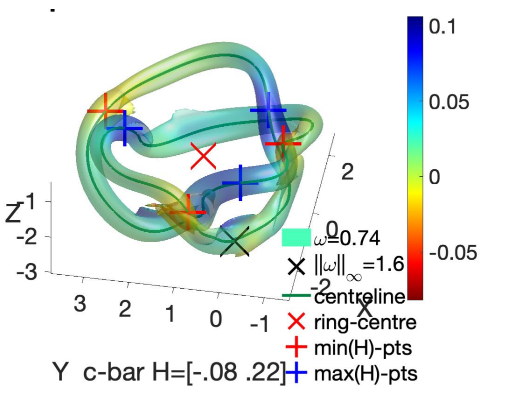

Figure 1. Trefoil $t = 24$ mid-reconnection vorticity isosurface painted with the helicity density h, Local $h < 0$ and local maxima and minima of h on the centreline are indicated.

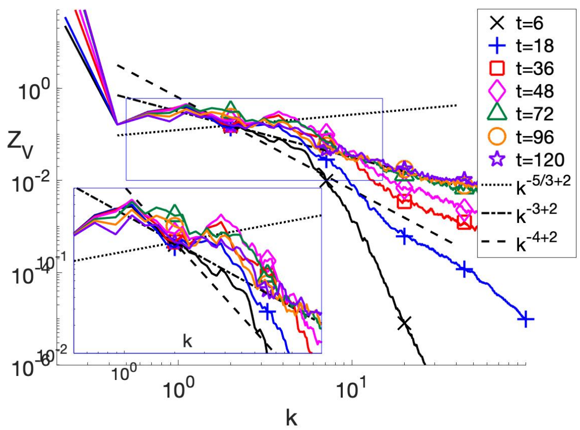

Figure 2. Enstrophy spectra over time. Power law overshoots $k^{-5/3+2}$ at $t = 36$ and 48, before settling to the Kolmogorov power law at $t = 72$ and 96. Reconnection finishes at $t_x \approx 41$.

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Wednesday 19 May 2021

Session 6

14:00 – 16:50

STATISTICAL PROPERTIES OF TURBULENCE IN THE PRESENCE OF A SMART SMALL-SCALE CONTROL

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By means of high-resolution numerical simulations, we compare the statistical properties of homogeneous and isotropic turbulence to those of the Navier-Stokes equation where small-scale vortex filaments are strongly depleted, thanks to a nonlinear extra viscosity acting preferentially on high vorticity regions, see Fig. 1 for a graphical illustration. We show that the presence of such smart small-scale drag can strongly reduce intermittency and non-Gaussian fluctuations on a range of scales much larger than the control spectrum. Our results pave the way towards a deeper understanding on the fundamental role of degrees of freedom in turbulence as well as on the impact of (pseudo)coherent structures on the statistical small-scale properties [1]. Our work can be seen as a first attempt to develop smart-Lagrangian forcing or drag mechanisms to control turbulence. Indeed, we aim to study the reaction of turbulence when smart-particles, driven by Reinforcement Learning algorithms [2], are activated with a positive/negative feedback only in strong vorticity filaments, intense strain, or other relevant regions. In this way one can ask questions such as: Is intermittency more sensitive to feedback on vorticity or strain? Or to strongly ascending/descending plumes in thermally stratified cases? Another fundamental aspect is the reconstruction of turbulent datasets from partial measurements, see [3]. We aim to learn how to coordinate smart-particles to engineer a multi-scale/multi-probing system that combined with tools as Lagrangian-Nudging, see [4], can improve the flow reconstruction. By the development of smart-particles able to navigate autonomously (following structures or accumulating in specific regions) we can ask questions about the quality and quantity of measurements needed to obtain a better reconstruction.

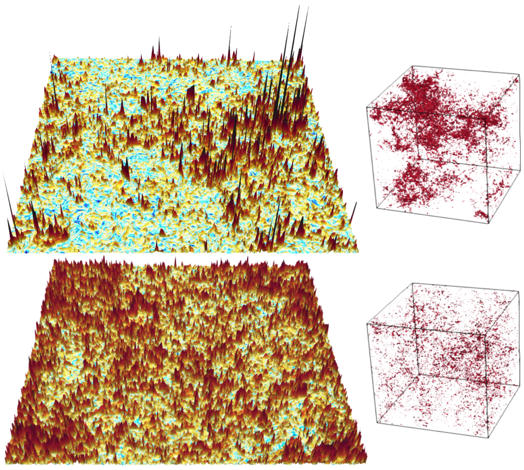

Figure 1. (Top row) Left: vorticity amplitude in a 2D plane, from a simulation without control term. Right: regions where the vorticity amplitude is above 20% of its maximum over the flow volume. (Bottom row) Left: visualisation of enstrophy plane from a simulation with active control term. Both visualisations are obtained using the same range in the color axis. Right: regions where the vorticity amplitude is above the control forcing threshold, fixed to 20% of the maximum value. Both simulations are performed with $N = 1024^3$ collocation points.

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EXPLORING CAUSALITY THROUGH SENSITIVITY IN HOMOGENEOUS ISOTROPIC TURBULENCE

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By running an unprecedentedly large number of direct numerical simulations (DNS) seeded with localized perturbations [1], we identify flow structures which are essential for the dynamics of homogeneous turbulence. The perturbations zero the velocity vector at a given point, and have a given length scale, making them reminiscent of the effect of the introduction of a obstacle in the flow. The probability distribution of the evolution of the perturbation norm as a function of time defines an optimal observation time, taken as the moment at which the ratio between the ninth and first deciles is maximum. The perturbations above the ninth decile at that time are considered causally significant for the flow (large impact) and the ones below the first, as irrelevant (marginal impact). The former modify the velocity field 10^4 more than the latter, in terms of the L_2-norm of the velocity difference. Tracing the relevant perturbations back to their starting location [2] uncovers important regions of the flow; allowing the classification of local flow structures based on their causal impact on turbulence dynamics, rather than on their instantaneous characteristics.
About 80% of the relevant structures are found to be elongated streams, and they are found to be a reasonable *a priori* marker for strong influence over the flow. Finally, the streams are located across the flow fields, and found to be connected to each other. The procedure uncovers the existence of previously ignored 'superstructure' of streams in the flow, whose disruption results in an important modification of the flow structure at a scale much larger than that of the original perturbations.

Funded by the Coturb grant ERC 2014.AdG-669505.

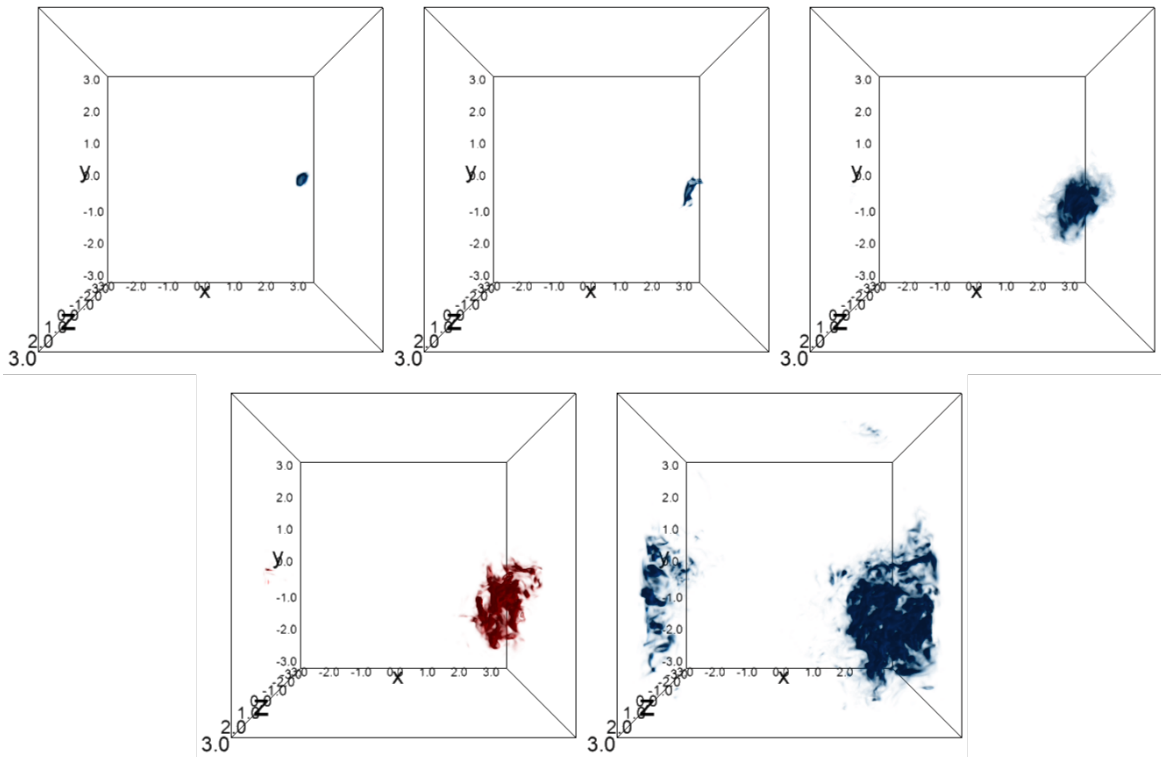

Figure 1. Snapshots from the evolution of a significant perturbation. The five snapshots are distributed equally across one eddy turnover time. The red snapshot roughly corresponds to the time of maximum significance.

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TURBULENCE WITHOUT VORTEX STRETCHING

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Vortex stretching plays a primordial role in the transfer of kinetic energy, and thereby the rate of dissipation. Our aim is to understand the effect of vortex stretching by removing this term from the Navier-Stokes equations and by comparing the results to the original system. The system we consider is thus

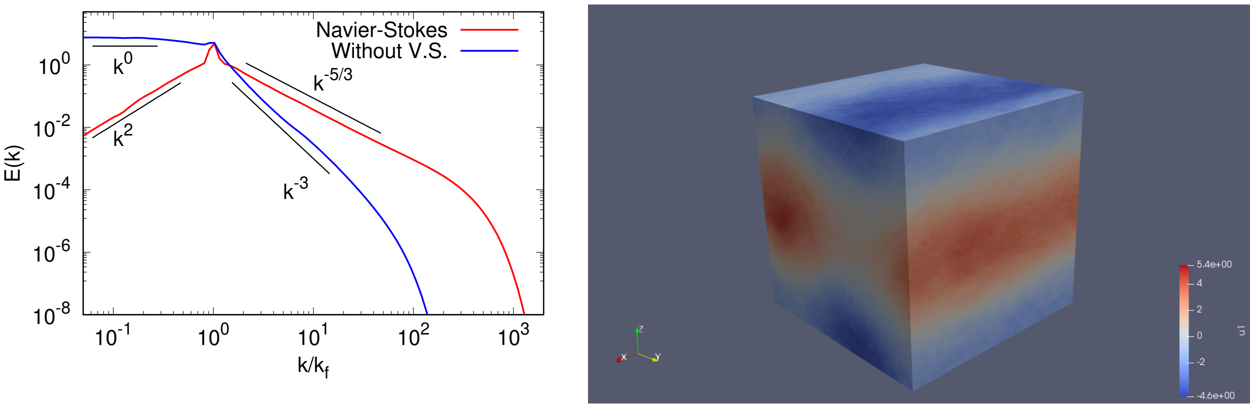
$$\frac{\partial \boldsymbol{\omega}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{\omega} = \lambda \boldsymbol{\omega} \cdot \nabla \boldsymbol{u} + \nu \Delta \boldsymbol{\omega}, \tag{1}$$

with $\boldsymbol{\omega} = \nabla \times \boldsymbol{u}$ and ν the viscosity. We compare the cases $\lambda = 1$ (conventional Navier-Stokes dynamics) and $\lambda = 0$ (3D flow without vortex stretching).

Note that the vortex stretching term is naturally eliminated in two-dimensional (2D) turbulence. Thereby the 3D system without vortex stretching builds a bridge between 2D and 3D turbulence. It is shown that the inviscid system conserves enstrophy, as 2D turbulence, and helicity, just like inviscid 3D turbulence. The associated cascades are assessed using pseudo-spectral Direct Numerical Simulations and two-point closure modeling [1].

The inviscid system relaxes to a force-free large-scale structure akin to an ABC flow, in contraxt to 3D turbulence, where no coherent large-scale structure is observed in the inviscid equilibrium state. The x-component of the velocity is shown in Fig. 1 from which we can see the coherent structure. Furthermore, the inviscid system relaxes towards an absolute equilibrium state for which we derive and assess analytical predictions.

The present system allows to explore similarities between 2D and 3D turbulence and in particular allows to underpin the exact role that vortex-stretching plays in three-dimensional turbulence. In particular, without vortex stretching, energy dissipation takes mainly place around the forcing scale. A question that we will try to reply on during the workshop is whether a small amount of vortex-stretching can restablish the energy cascade towards small scales and how this relates to the intermittent nature of small-scale fluctuations.



(a) (b)

Figure 1. (a) Energy spectrum comparing the system without vortex-stretching to Navier-Stokes turbulence (EDQNM results). (b) Visualizations of the velocity in the x-direction for the truncated inviscid system without vortex stretching (DNS results).

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PREDATOR-PREY MODELING OF LARGE-SCALE ENERGY FLUCTUATIONS IN TURBULENCE

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Small scale turbulence is piloted by the energy injection at large scales. Fluctuations of energy at the large scales are giving rise, in a finite time, to important fluctuations of the viscous dissipation [1]. We unveil a predator-prey type mechanism, which leads to quasi-periodic fluctuations and bursts of the dissipation in a linearly forced turbulence.
We conduct a direct numerical simulation of linearly forced turbulence in a $(2\pi)^3$ periodic box using the Fourier spectral method. The governing equations are the incompressible Navier-Stokes equations,

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} = -\frac{1}{\rho}\boldsymbol{\nabla} p + \nu \nabla^2 \boldsymbol{u} + f_0 \boldsymbol{u}'_{\perp}, \quad \boldsymbol{\nabla} \cdot \boldsymbol{u} = 0, \tag{1}$$

where $\boldsymbol{u} = (u_x, u_y, u_z)$ and p are velocity and pressure fields, respectively. We set the fluid density ρ and the forcing coefficient f_0 to be unity and vary the kinematic viscosity ν. We apply the forcing to the horizontal fluctuating velocity field $\boldsymbol{u}'_{\perp} = (u_x - \langle u_x \rangle, u_y - \langle u_y \rangle, 0)$, where $\langle \cdot \rangle$ denotes the spatial average.
Figure 1 shows the time series of energy $E = \left\langle \boldsymbol{u}^2 \right\rangle /2$ for $\nu = 0.4$ along with its horizontal and vertical components, $E_\perp = \left\langle \boldsymbol{u}_\perp^2 \right\rangle /2$ and $E_z = \left\langle u_z^2 \right\rangle /2$, respectively. The distributions of $\sqrt{\boldsymbol{\omega}^2}$, where $\boldsymbol{\omega} = \boldsymbol{\nabla} \times \boldsymbol{u}$, are also shown.

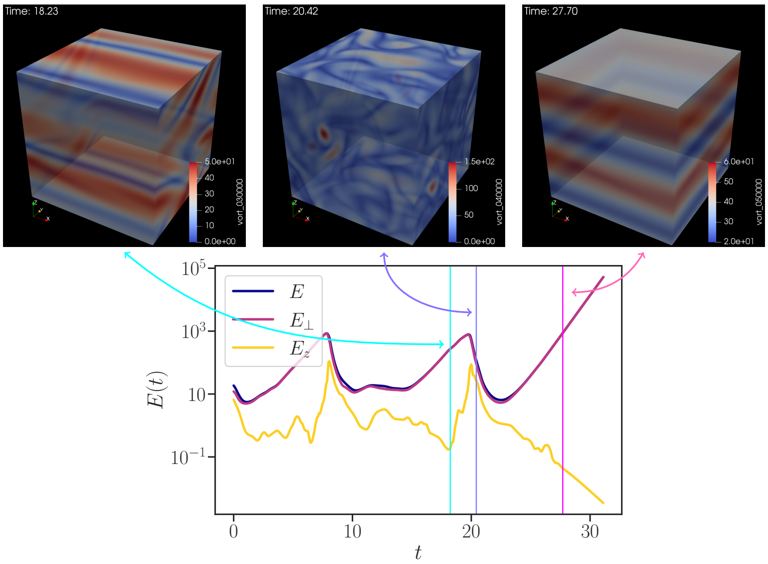

Figure 1. Time series of E, $E_\perp$ and E_z in semi-log plot along with the distributions of $\sqrt{\boldsymbol{\omega}^2}$ at three instances.

Exponential increase of $E_\perp$ followed by exponential decrease of E_z suggests that there might be a predator-prey relation between the two components. In this description, $E_\perp$ is a prey directly driven by the forcing and E_z is a predator energized by the prey. Vortical structures visualized by $\sqrt{\boldsymbol{\omega}^2}$ shows horizontal and 3D structures during the cycle.
Another interesting feature is the blow-up of energy, which we have verified to be independent of the numerical resolution. It originates in a two-dimensionalization of the flow, possibly related to the idea of the sudden relaminarization [2] of turbulence.
In the colloquium, we will show how these dynamics can be described by a simple Lotka-Volterra limit cycle. Furthermore, we will show how these large-scale predator-prey dynamics give rise to large fluctuations of the viscous dissipation rate, and we will also discuss the spatial structures of the relevant quantities.

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HIGHLY CAUSAL EVENTS IN TURBULENT CHANNEL FLOW

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The central hypothesis of this abstract is that turbulence is sustained by discrete events that determine its temporal development. Such events are causal to the flow in the sense that the future state of the flow changes a lot when and only when they appear. They are key to understanding the non-stationary nature of turbulence. In this study, highly causal flow features of turbulent channel flow are studied by a Monte-Carlo approach [1]. The basic idea is that perturbing causal events results in making the future very different. Direct numerical simulation of open channel flow at friction Reynolds number $Re_\tau = 608$ is used. The computational domain is a doubly periodic box of size $L_x \times L_y \times L_z = \pi h \times h \times \pi h$, where x, y, z and h denotes streamwise, wall-normal, spanwise direction and channel height respectively. Following a previous study of 2D isotropic turbulence in [1], a small part of the flow (cell) is perturbed, and the flow is temporally developed. The causal significance of the perturbed cell is measured by the domain-integrated L_2 norm of the velocity difference between the perturbed and unperturbed flows, and is generally a function of time. Thus, highly causal cells are identified at the time, τ_{max}, when the significance ratio between the best and worst sample is maximum. Measurements are done for many initial snapshots and cell positions, and the flow features common to the causally significant cells are evaluated from the ensemble of those realizations. In this study, the flow is perturbed by zeroing the fluctuation velocity in a cubic cell. Because the flow is inhomogeneous in the wall-normal direction, causal significance is sensitive to the central height of the cell, y_{box}, and is only compared among cells with the same y_{box}. Up to 12 different heights, ranging from wall-attached to $y^+_{box} = 300$, and five cell sizes, $l^+_{box} = 25$, 50, 75, 100 and 150, are examined in this study, where the '+' superscript denotes normalization by the friction length.

The causal effect grows more slowly away from the wall than near it. Figure 1 shows the temporal development of the $x - z$ averaged perturbation. When the near wall is perturbed (left), the perturbation immediately grows and propagates towards the centre. On the other hand, when the middle of the domain is perturbed (right), the perturbation initially propagates in both wall-normal directions, but grows little. Only after it reaches the wall, it starts to grow by several orders of magnitude, and eventually propagates back to the centre. The significance ratio increases as the initial cell moves higher, suggesting that the causal effect is more intermittent away from the wall. Highly causal cells are found to be associated with intense gradients, such as enstrophy and strain rate. Interestingly, this tendency is independent of the cell size in the range given above. Among the three velocity components, the wall-normal velocity is most closely associated with significance, underscoring the importance of the vertical propagation for the causal events.

Funded by the Coturb grant ERC 2014.AdG-669505.

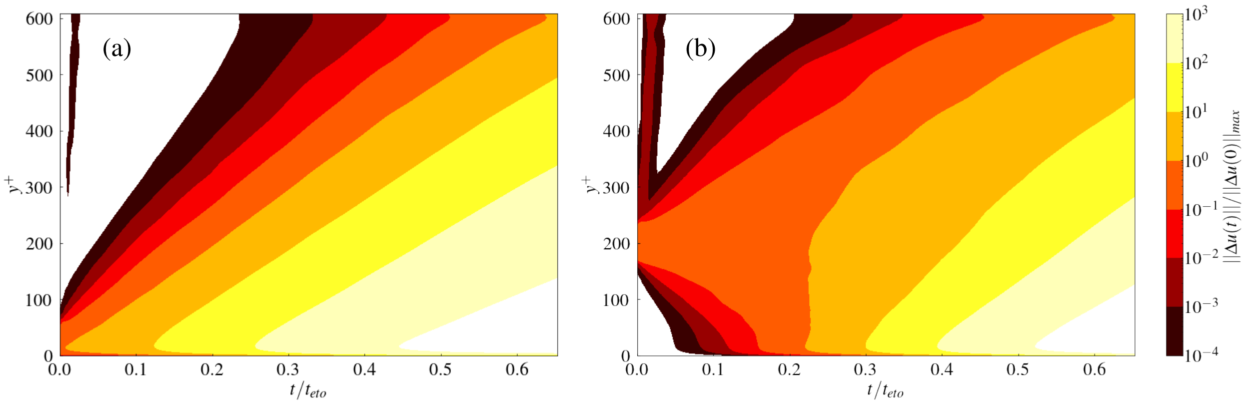

Figure 1. Contour plot of the temporal development of $x - z$ averaged perturbation. Time is normalized by eddy-turnover time $t_{eto} = h/u_\tau$, where u_τ is the friction velocity. Contour levels are normalized by the maximum perturbation at the initial snapshot. $l^+_{box} = 50$. (a) $y^+_{box} = 25$ (attached to the wall), (b) $y^+_{box} = 200$.

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