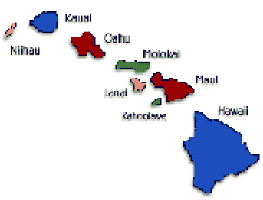
Turbulence Colloquium at Mauna Kea (TCM 2017)

Recent Advances in Turbulence Research

98th Annual Meeting
Hawai`i Preparatory Academy
Waimea, Big Island, Hawai`i
June 19 - 23, 2017



AAAS Pacific Division

Photographer: Masako Okamoto

Organizers: Frank G. Jacobitz, Kai Schneider and Katsunori Yoshimatsu

http://www.cmi.univ-mrs.fr/~kschneid/tcm_2017_poster+abstracts.pdf

Program TCM 2017

Turbulence Conference at Mauna Kea (TCM-2017): Recent Advances in Turbulence Research

ENERGY LAB
Tuesday
8:15 a.m. – 3:00 p.m.
continues on Thursday
8:15 a.m. – 3:00 p.m.
and continues again on Friday
8:30 a.m. – 3:00 p.m.

Program organized by: *Frank G. Jacobitz* (Mechanical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego), *Kai Schneider* (Institut de Mathématiques de Marseille (I2M) du Centre de Mathématiques et d'Informatique, Aix-Marseille Université, Marseille, France and *Katsunori Yoshimatsu* (Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan).

Program sponsored by the Pacific Division Section on Engineering, Technology, and Applied Sciences.

The turbulent motion of fluids is an important mechanism for the transport and mixing in many engineering applications and geophysical environment. This symposium includes work on recent advances in turbulence research from theoretical, experimental, and field studies. In addition to oral and poster presentations in the mornings, the symposium will include time for discussions and joint work during the afternoon and evenings of the conference days.

Session Chair: *Frank G. Jacobitz*

8:15 *Welcome*

8:30 **6** *Transitional-Turbulent Spots and Turbulent-Turbulent Spots in Boundary Layer*, **JAMES M. WALLACE[1]*, XIAOHUA WU[2], PARVIZ MOIN[3], JINHIE SKARDA[3], ADRIAN LOZANO-DURAN[3], and JEAN-PIERRE HICKEY[2]** ([1]Department of Mechanical Engineering, University of Maryland, College Park, MD; [2]Department of Mechanical and Aerospace Engineering, Royal Military College of Canada, Kingston, ON, Canada; [3]Center for Turbulence Research, Stanford University, Stanford, CA).

9:20 **7** *Influence of Small but Finite Viscosity on the Statistics in the Log-Law Region of Wall-Bounded Turbulence*, **YUKIO KANEDA (**Department of Natural Science, Aichi Institute of Technology, Toyota, Japan).

10:00 **BREAK**

<u>***10:30***</u> **8** *On the Structure Orientation in Homogeneous Turbulent Shear Flows, Part I: Analysis Method Development*, **ADAM F. MOREAU[1]*, JOYLENE C. AGUIRRE[2], FRANK G. JACOBITZ[2]** ([1]Electrical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, San Diego, CA; [2]Mechanical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, San Diego, CA).

<u>***10:50***</u> **9** *On the Structure Orientation in Homogeneous Turbulent Shear Flows, Part II: Application to Stratified and Rotating Shear Flows*, **JOYLENE C. AGUIRRE[1]*, ADAM F. MOREAU[2], FRANK G. JACOBITZ[1]** ([1]Mechanical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, San Diego, CA; [2]Electrical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, San Diego, CA).

11:10 **10** *On the Scale-Dependent Helicity in Stably Stratified Turbulent Shear Flows*, **FRANK G. JACOBITZ[1]*, KAI SCHNEIDER[2], and MARIE FARGE[3]** ([1]Mechanical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, San Diego, CA; [2]Institut de Mathématiques de Marseille, Aix-Marseille Université, Marseille, France; [3]Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure and Paris Sciences et Lettres, Paris, France)**.**

11:45 **LUNCH**

1:30 *Round Table: Questions and Perspectives*

3:00 **BREAK**

Symposium continues Thursday morning at 8:15 a.m.
Please refer to page 37 of these Proceedings for schedule.

Turbulence Conference at Mauna Kea (TCM-2017): Recent Advances in Turbulence Research

ENERGY LAB
Thursday
8:15 a.m. – 3:00 p.m.
continues Friday
8:30 a.m. – 3:00 p.m.

This symposium is continuing from Tuesday.

Program TCM 2017

Please refer to page 31 of these Proceedings for details.

Session Chair: *Kai Schneider*

8:15 **35** *Rotating Rayleigh-Bénard Convection: Recent Developments and a Lagrangian Perspective*, **HERMAN J.H. CLERCX** (Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands).

9:05 **36** *Universal Aspects of Contravariant and Covariant Vector Elements in Turbulent Flows*, **KIYOSI HORIUTI*, KOUDAI MATSUSHITA, and YOSHINORI TSUDA** (Department of Mechano-Aerospace Engineering, Tokyo Institute of Technology, Tokyo, Japan).

9:40 **37** *Ocean Surface Stress Feedback in Tropical Cyclones and Over Frontal Eddies*, **W. TIMOTHY LIU*, XIAOSU XIE, and WENQING TANG** (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA).

10:00 **BREAK**

10:25 **38** *Global Flow Generation and Angular-Momentum Transport by Turbulent Helicity*, **NOBUMITSU YOKOI** (Institute of Industrial Science, University of Tokyo, Tokyo, Japan).

11:00 **39** *Wavelet Regularization of Three-dimensional Incompressible Euler Flows*, **NAOYA OKAMOTO[1]*, MARIE FARGE[2], KAI SCHNEIDER[3], and KATSUNORI YOSHIMATSU[4]** ([1]Center for Computational Science, Nagoya University, Nagoya, Japan; [2]Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure and Paris Sciences et Lettres, Paris, France; [3]Institut de Mathématiques de Marseille, Aix-Marseille Université, Marseille, France; [4]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan).

11:20 **40** *Anisotropic Pressure Correlation Spectra in Turbulent Boundary Layer*, **YOSHIYUKI TSUJI[1]* and YUKIO KANEDA[2]** ([1]Department of Energy Engineering and Science, School of Engineering, Nagoya University, Nagoya, Japan; [2]Department of Natural Science, Aichi Institute of Technology, Toyota, Japan).

11:55 **LUNCH**

1:30 *Round Table: Questions and Perpectives*

3:00 **BREAK**

Symposium continues Friday morning at 8:30 a.m.
Please refer to page 45 of these Proceedings for schedule.

Turbulence Conference at Mauna Kea (TCM-2017): Recent Advances in Turbulence Research

ENERGY LAB
Friday
8:30 a.m. – 3:00 p.m.

This symposium is continuing from Thursday.
Please refer to page 37 of these Proceedings for details.

Session Chair: *Katsunori Yoshimatsu*

8:30 **93** *Passive Scalar Spectrum and Intermittency Effects at Very High Schmidt Number*, **TOSHIYUKI GOTOH* and ISUMI SAITO** (Department of Physical Science and Engineering, Nagoya, Institute of Technology, Nagoya, Japan).

9:20 **94** *Multiscale Statistics of Trajectories with Applications to Football Players and Particles in Fluid Turbulence*, **KAI SCHNEIDER[1]*, BENJAMIN KADOCH[2], and WOUTER BOS[3]** ([1]Institut de Mathématiques de Marseille, Aix-Marseille Université, Marseille, France; [2] IUSTI-CNRS, Aix-Marseille Université, Marseille, France; [3] LMFA-CNRS Ecole Centrale de Lyon, Université de Lyon, Ecully, France).

9:50 **BREAK**

10:25 **95** *Scale Similarity of the Particle Clustering in the Inertial Range of Turbulence*, **TAKETO ARIKI[1]*, KYO YOSHIDA[2], KEIGO MATSUDA[3], and KATSUNORI YOSHIMATSU[1]** ([1]Institute for Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan; [2]Institute of Physics, Faculty of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan; [3]Center for Earth Information Science and Technology, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan).

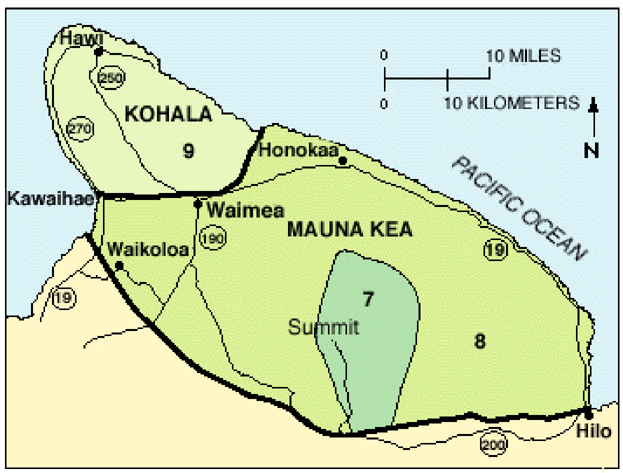
11:00 **96** *Enhancement of Cloud Radar Reflectivity Factor Due to Turbulent Clustering of Settling Water Droplets*, **KEIGO MATSUDA*, RYO ONISHI, and KEIKO TAKAHASHI** (Center for Earth Information Science and Technology, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan).

11:35 **97** *Settling of (Non-)Heavy Inertial Particles in Turbulence*, **HERMAN J.H. CLERCX***, **MICHEL A.T. VAN HINSBERG** , and **FEDERICO TOSCHI** (Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands).

11:55 **LUNCH**

13:30 *Round Table: Questions and Perspectives*

3:00 **BREAK**



AAAS Pacific Division

2017 Hawai`i Meeting
Symposium Abstracts

Turbulence Colloquium at Mauna Kea (TCM 2017): Recent Advances in Turbulence Research

Transitional-Turbulent Spots and Turbulent-Turbulent Spots in Boundary Layer, **JAMES M. WALLACE[1]*, XIAOHUA WU[2], PARVIZ MOIN[3], JINHIE SKARDA[3], ADRIAN LOZANO-DURAN[3], and JEAN-PIERRE HICKEY[2]** ([1]Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA; [2]Department of Mechanical and Aerospace Engineering, Royal Military College of Canada, Kingston, ON K7K 7B4, Canada; [3]Center for Turbulence Research, Stanford University, Stanford, CA 94305-3035, USA; wallace@umd.edu).

Two new and striking observations about the canonical zero pressure gradient, smooth, flat plate boundary layer are presented here. The first is that, for bypass transition with the superposition on a Blasius boundary layer by a continuous freestream flow of homogeneous isotropic turbulence, we found that the transitional-turbulent spot inception mechanism is analogous to the secondary instability of boundary layer natural transition, namely, a spanwise vortex filament becomes a Λ vortex and then a hairpin packet. Long streak meandering does occur, but usually when a streak is infected by a nearby existing transitional-turbulent spot. Streak waviness and breakdown is therefore not the mechanism for the inception of transitional-turbulent spots found here. Rather, they only facilitate the growth and spreading of existing transitional-turbulent spots. The second striking new observation is the discovery, in the inner layer of the developed turbulent boundary layer, of what we call turbulent-turbulent spots. These are dense concentrations of small-scale vortices with high swirling strength originating from hairpin packets. Although structurally quite similar to the transitional-turbulent spots, these turbulent-turbulent spots are generated locally in the fully-turbulent environment, and they are persistent with a systematic variation of detection threshold level. They exert indentation, segmentation and termination on the viscous sublayer streaks, and they coincide with local concentrations of high levels of Reynolds shear stress, enstrophy and temperature fluctuations. The sublayer streaks seem to be passive and are often simply the rims of the indentation pockets arising from the turbulent-turbulent spots. Our evidence for both of these new phenomena is drawn from a thoroughly validated spatially-developing direct numerical simulation.

Influence of Small but Finite Viscosity on the Statistics in the Log-Law Region of Wall-Bounded Turbulence, **YUKIO KANEDA (**Department of Natural Science, Aichi Institute of Technology, 470-0392, Yachikusa, Yakusa-cho, Toyota, Japan; ykaneda@aitech.ac.jp).

The log-law for the mean velocity in wall-bounded turbulence is derived by assuming that the viscosity is small enough so that its (direct) influence on the statistics in the log-law region is negligible. However, in real turbulence, the viscosity is not zero but finite, although it may be very small. In the talk, a discussion is given on the influence of the small but finite viscosity on the statistics in the log-law region, from the view point of Linear-Response-Theory (LRT). In the theory, the effect of the viscosity is regarded as a disturbance added to a certain basic state that is supposed to be realized in the limit of infinitely small viscosity. The similar idea is applicable also to the influence of small but finite viscosity on the statistics in the so-called universal equilibrium region at mall scales in high Reynolds number turbulence.

On the Structure Orientation in Homogeneous Turbulent Shear Flows, Part I: Analysis Method Development, **ADAM F. MOREAU[1]*, JOYLENE C. AGUIRRE[2], FRANK G. JACOBITZ[2]** ([1]Electrical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, 5998 Alcalá Park, San Diego, CA 92110, USA, adammoreau@sandiego.edu; [2]Mechanical Engineering Department, Shiley-Marcos School of

Engineering, University of San Diego, 5998 Alcalá Park, San Diego, CA 92110, USA, joyleneaguirre@sandiego.edu, jacobitz@sandiego.edu).
Direct numerical simulations were performed to study the orientation of flow structures in homogeneous turbulent shear flows. The incompressible Navier-Stokes equations were solved in the Rogallo frame with periodic boundary conditions and isotropic initial conditions. A spectral method was used for the spatial discretization and the solutions were advanced in time with a fourth-order Runge-Kutta method. Flow structures inclined in the vertical direction are observed in instantaneous fields of velocity magnitude and vorticity magnitude. The three-dimensional two-point autocorrelation coefficient of velocity magnitude and vorticity magnitude is computed to quantify the orientation of flow structures. Isosurfaces of the autocorrelation coefficient closely resemble an inclined ellipsoid, which is directly related to the inclination angle of the flow structures in the vertical direction. A least-squares fit of an ellipsoid to the isosurface was performed and the major and minor axes were determined. From the major and minor axes, the inclination angle of flow structures was determined. The inclination angle was found to depend upon the choice of autocorrelation coefficient value for very low and very high values. However, the inclination angle reached a band of constant values for non-extreme choices of isovalue. At low autocorrelation coefficient values (about 0 to 0.3), the isosurface no longer represents the structure orientation and the surface is non-ellipsoid. At high autocorrelation coefficient values (about 0.7 to 1), the number of data points making up the isosurface decreased such that the inclination angle is no longer well-defined. Within the band of constant values (about 0.3 to 0.8) averaging was conducted to reduce uncertainty due to the use of a particular autocorrelation coefficient value. The inclination angle of flow structures in homogeneous turbulent shear flows was determined to be XX.X° or YY.Y° with the analysis based on the two-point autocorrelation coefficient isosurfaces of velocity magnitude or vorticity magnitude, respectively.

On the Structure Orientation in Homogeneous Turbulent Shear Flows, Part II: Application to Stratified and Rotating Shear Flows, **JOYLENE C. AGUIRRE[1]*, ADAM F. MOREAU[2], FRANK G. JACOBITZ[1]** ([1]Mechanical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, 5998 Alcalá Park, San Diego, CA 92110, USA, joyleneaguirre@sandiego.edu, jacobitz@sandiego.edu; [2]Electrical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, 5998 Alcalá Park, San Diego, CA 92110, USA, adammoreau@sandiego.edu).

Based on the results of two series of direct numerical simulations, the effect of stratification and rotation on the orientation of flow structures is investigated in homogeneous turbulent shear flows. For stably stratified shear flows, the Richardson number is varied from Ri = 0 to Ri = 10. The growth rate of the turbulent kinetic energy is observed to decrease with increasing Richardson number. Similarly, the inclination angle of flow structures in stratified shear flow decrease with increasing Richardson number and are dependent on the growth rate of kinetic energy. For rotating shear flows, nine cases are considered: turbulent shear flow without rotation, with moderate rotation, and with strong rotation, where the rotation configuration is either parallel or antiparallel. The Coriolis parameter to shear rate ratio f /S is varied from −10 to 10. Positive values of f/S correspond to an anti-parallel configuration, while negative values correspond to a parallel configuration between the system rotation and the mean flow vorticity. The strongest growth rate of the turbulent kinetic energy is observed for f /S = +0.5, while the growth rate is less than that for the flow without rotation and for f /S = −0.5. Strong rotation results in strong decay of the turbulent kinetic energy. The inclination angle is observed to reach a maximum value in the anti-parallel configuration with moderate rotation with f/S = +05 and to be reduced in the parallel configuration with moderate rotation. The strongly rotating cases result in smaller inclination angles, which are almost independent of the flow configuration. Therefore, the inclination angle of flow structures appears to be directly related to the dynamics of the flow.

On the Scale-Dependent Helicity in Stably Stratified Turbulent Shear Flows, **FRANK G. JACOBITZ[1]*, KAI SCHNEIDER[2], and MARIE FARGE[3]** ([1]Mechanical Engineering Department, Shiley-Marcos School of Engineering, University of San Diego, 5998 Alcalá Park, San Diego, CA 92110, USA, jacobitz@sandiego.edu; [2]Institut de Mathématiques de Marseille, Aix-Marseille Université, 39 rue Joliot-Curie, 13453 Marseille Cedex 13, France, kai.schneider@univ-amu.fr; [3]Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure and Paris Sciences et Lettres, 24 rue Lhomond, 75231 Paris Cedex 5, France, marie.farge@ens.fr).

The properties of scale-dependent helicity in homogeneous turbulence with shear and stable stratification are studied. Direct numerical simulations are performed, in which the Richardson number is varied from Ri = 0, corresponding to unstratified shear flow, to Ri = 1, corresponding to strongly stratified shear flow. After an initial decay due to the isotropic initial conditions, growth of the turbulent kinetic energy is observed for small Richardson numbers and decay for strong stratification. The eventual evolution of the turbulent kinetic energy is found to change from growth to decay at a critical Richardson number of about $Ri_{cr} \approx 0.15$. In order to study the scale-dependent helical properties of the flows, the velocity field u and the vorticity field ω are decomposed into scale-dependent components u_j and ω_j at scale 2^{-j} using a wavelet-based approach. The scale-dependent relative helicity, corresponding to the cosine of the angle between u_j and ω_j, is then computed as $h_j = u_j \cdot \omega_j / (||u_j||\ ||\omega_j||)$. In the weakly stratified case, turbulent motions at larger scales (smaller j) show a preference for locally two-dimensional motion with $h_j = 0$. At smaller scales (larger j), however, a preference for helical motion with $h_j = \pm 1$ is found. In the strongly stratified case, however, all scales of motion show a preference for helical motion with $h_j = \pm 1$. These observations are consistent with the previous results obtained for rotating and sheared homogeneous turbulence.

Rotating Rayleigh-Bénard Convection: Recent Developments and a Lagrangian Perspective, **HERMAN J.H. CLERCX** (Department of Applied Physics (Building CC 2.19), Eindhoven University of Technology, PO Box 513, 5600MB, Eindhoven, The Netherlands, h.j.h.clercx@tue.nl).

Turbulent convection in geophysical and astrophysical flows and in several engineering applications is dramatically affected by system rotation. Although (turbulent) rotating convection has received considerable attention during the last decades it is since about 10 years ago that the interest in this topic has increased strongly once again. This is due to the observation of new phenomena such as transitions between turbulent states and sudden heat transport enhancement by passing a critical rotation rate, combined with the development of advanced optical diagnostics to explore turbulence and the huge increase in computing power for simulations. Moreover, both numerically and experimentally the regime of geostrophic convection, relevant for geophysical and astrophysical (turbulent) convection, can currently be touched opening up a regime which contains some further surprises. With this contribution I will introduce the basic concepts and mechanisms active in rotating turbulent convection, discuss some of the recent developments, and present results of a Lagrangian analysis (based on 3D Particle Tracking Velocimetry measurements supported by DNS) of turbulent rotating convection with emphasis on statistical anisotropy and how Lagrangian statistics of velocity, acceleration and curvature of particle trajectories is affected by rotation.

Universal Aspects of Contravariant and Covariant Vector Elements in Turbulent Flows, **KIYOSI HORIUTI, KOUDAI MATSUSHITA, and YOSHINORI TSUDA** (Department of Mechano-Aerospace Engineering, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku Tokyo, 152-8552, JAPAN, ~81 3 5734 2638; khoriuti@mes.titech.ac.jp).

The vector fields which govern the transport of fluids in turbulence can be divided into two categories as the contravariant vector and covariant vector. Representative contravariant vectors are the velocity, vorticity, magnetic field, e.t.c, while representative covariant vectors are the pressure gradient, scalar gradient, Lorentz force, and so on. In general, it appears that the covariant vectors exhibit stretching larger than the contravariant vectors. For example, the probability density function of scalar dissipation which is the inner product of the scalar gradient vectors shows the tail longer than the byproduct of the vorticity vector, or enstrophy. Here, stretching of vorticity vector saturates at an intermediate length and stretching is terminated when it attains the length smaller than the corresponding length of scalar gradient. Thus, cascade of energy in the scalar persists to the scales smaller than those of the fluid. The governing equation of the contravariant and covariant vectors consists of the upper and lower convective derivatives, respectively. It may be considered that the difference in the stretching of these vectors and generation of energy cascade is attributed to the features of these convective derivatives. This study aims to conduct an analysis on the elongation of contravariant and covariant vectors and generation of energy cascade.

In this talk, we will discuss on the viscoelastic turbulent flows diluted with the polymers, the magneto-hydrodynamics (MHD) turbulence and the passive scalar transport. In the viscoelastic turbulence, we show the results from the multi-scale analysis. We studied elongation and energy-transfer process of polymers dispersed in the homogeneous isotropic turbulence by connecting mesoscopic Brownian description of elastic dumbbells to macroscopic description for the solvent (DNS). The dumbbells are allowed to be advected either affinely with the macroscopically-imposed deformation or completely non-affinely. The dumbbell connector vector becomes contravariant in the former case and covariant in the latter. It is shown that highly-elongated contravariant polymers remove more energy from the large scales than they can dissipate and transfer the excess energy back into the solvent. In the highly-stretched covariant polymers, the energy cascade into the polymer is sustained. Using the approximate solution for the elastic energy production term, we identified the term which is primarily responsible for causing this transfer as the skewness of the strain-rate tensor, $-S_{ik}S_{kj}S_{ji}$. It is shown that the energy transfer generated by the upper and lower convective derivatives can be distinguished using the decomposition of the strain skewness in the eigenvalues of the strain-rate tensor. We show that this decomposition provides general description for the stretching of the magnetic field vector in MHD and the scalar gradient vector and associated energy transfer.

Ocean Surface Stress Feedback in Tropical Cyclones and Over Frontal Eddies, **W. TIMOTHY LIU*, XIAOSU XIE, and WENQING TANG** (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, w.t.liu@jpl.nasa.gov, xiaosu.xie@jpl.nasa.gov, wenqing.tang@jpl.nasa.gov).

Stress is the turbulent transfer of momentum between the ocean and atmosphere. There was almost no direct stress measurement at the ocean surface except in dedicated field campaigns, and the stress we used were almost entirely derived from wind measurements using a drag coefficient, until the launch of the scatterometers. Scatterometers measure radar emission backscattered from ocean surface roughness, which is believed to be in equilibrium with local stress, but scatterometers have been promoted as a wind vector sensors. There were large uncertainties of the drag coefficients over the strong winds of tropical cyclones because of the lack of stress measurements. The wind vectors retrieved from the operating scatterometers also saturate at strong winds. We postulated that the saturation is an air-sea interaction problem and not a sensor problem. Under this assumption, we applied a stress retrieval algorithm developed over a moderate wind range, where abundant coincident in situ and satellite data are available, to retrieve stress under the strong winds of TCs. Using 0.9 million coincident scatterometer stress and in situ wind pairs in tropical cyclones, we showed that the drag coefficient decreases with wind speed at a much steeper rate than previously revealed, for wind speeds over 25 m/s. The result implies that the ocean applies less drag to inhibit TC intensification and the TC causes less ocean mixing and surface cooling than previous studies indicated. Turbulence at ocean surface is generated/suppressed by wind shear (the difference between wind and current) and buoyancy (vertical density stratification). Over ocean eddies, scatterometer stress vectors have rotation (vorticity) opposite to the surface currents, which is the results of wind shear. Scatterometer stress also show down-wind distribution of convergence centers, and cross wind vorticity centers around the eddies, as result of buoyancy. The combined shear and buoyancy turbulence generation affect feedback of stress on ocean energy input and Ekman pumping.

Global Flow Generation and Angular-Momentum Transport by Turbulent Helicity, **NOBUMITSU YOKOI** (Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro, Tokyo 153-8505, Japan; nobyokoi@iis.u-tokyo.ac.jp).

Turbulent helicity (velocity-vorticity correlation) represents breaking mirror-symmetry in turbulence. An expression of the Reynolds stress in non-mirror-symmetric turbulence is derived from the fundamental equations of hydrodynamics. In the expression, helicity gradient enters the Reynolds stress as the coupling coefficient of the mean absolute vorticity Ω (system rotation and mean relative vorticity). Using the analytical expression, a turbulence model (helicity model) is constructed. The helicity model is validated with the aid of a direct numerical simulation of rotating turbulence with helical forcing. This result implies that, inhomogeneous turbulent helicity coupled with the mean absolute vorticity Ω induces a global flow in the direction of Ω. This effect is generic in rotating turbulence with inhomogeneous helicity, and is expected to be relevant to several astro- and geo-physical flows, which include cyclones and solar convective motion. The angular-momentum transport in the solar convection zone is discussed as an interesting application of this effect.

Wavelet Regularization of Three-dimensional Incompressible Euler Flows, **NAOYA OKAMOTO[1*], MARIE FARGE[2], KAI SCHNEIDER[3], and KATSUNORI YOSHIMATSU[4]** ([1]Center for Computational Science, Nagoya University, Nagoya, 464-8603, Japan, n.okamoto@nagoya-u.jp; [2]Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure and Paris Sciences et Lettres, 24 rue Lhomond, 75231 Paris Cedex 5, France, marie.farge@ens.fr; [3]Institut de Mathématiques de Marseille, Aix-Marseille Université, 39 rue Joliot-Curie, 13453 Marseille Cedex 13, France, kai.schneider@univ-amu.fr; [4]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, 464-8603, Japan, yosimatu@imass.nagoya-u.ac.jp)**.**

We present numerical simulations of the three-dimensional incompressible Euler equations that we integrate while applying a wavelet-based denoising. At each time step the vorticity field is thus decomposed into wavelet coefficients, that are splitted between strong and weak coefficients, before reconstructing them in physical space to obtain the coherent and incoherent vorticities which are both multiscale and orthogonal within each other. Then, by using the Biot-Savart's kernel, one obtains the coherent and incoherent velocities. The coherent flow is advanced in time, while the noise-like incoherent flow is filtered out to model turbulent dissipation, which corresponds to adaptive viscous regularization. A safety zone in wavelet coefficient space is added to the coherent wavelet coefficients in order to track the flow evolution in scale and space. It is shown that the coherent flow indeed exhibits an intermittent turbulent nonlinear dynamics and a $k^{-5/3}$ energy spectrum, where k is the wavenumber. We assess the properties of the wavelet regularized Euler flows by comparing them to the Navier-Stokes turbulent flows. We then also compare them to Euler flows with either hyperviscous regularization or dispersive Euler-Voigt regularization, by adjusting the parameters to obtain dissipative effects that correspond to similar Reynolds numbers.

Anisotropic Pressure Correlation Spectra in Turbulent Boundary Layer, **YOSHIYUKI TSUJI[1] and YUKIO KANEDA[2]** ([1]Department of Energy Engineering and Science, Scholl of Engineering, Nagoya University, Chikusa-ku, Furo-cho, Nagoya city 464-8603, Japan, c42406a@nucc.cc.nagoya-u.ac.jp; [2]Department of Natural Science, Aichi Institute of Technology, Yachikusa 1247, Yakusa, Toyota 470-0392, Japan, ykaneda@aitech.ac.jp).

We measured the correlation spectrum $\hat{Q}_p(\vec{k})$ of pressure fluctuations in a turbulent boundary layer by a pressure probe with spatial and temporal resolutions that are sufficient to analyse inertial subrange statistics. The influence of the mean velocity gradient and the solid wall is studied using an idea similar to what underlies the linear response theory developed in statistical mechanics for systems at or near thermal equilibrium. If we write the spectrum $\hat{Q}_p(\vec{k})$ as $\hat{Q}_p(\vec{k}) = \hat{Q}_p^{(0)}(\vec{k}) + \Delta\hat{Q}_p(\vec{k})$, where $\hat{Q}_p^{(0)}(\vec{k})$ is the isotropic Kolmogorov spectrum in the absence of mean shear, then the deviation $\Delta\hat{Q}_p(\vec{k})$ due to the mean shear and solid wall is approximately linear and is determined by a few non-dimensional universal constants in addition to shear stress tensor S_{ij}, wave number k, distance from the wall y ,and the mean energy dissipation rate.

Passive Scalar Spectrum and Intermittency Effects at Very High Schmidt Number, **TOSHIYUKI GOTOH* and ISUMI SAITO** (Department of Physical Science and Engineering, Nagoya, Institute of Technology, Showa-ku, Nagoya, 466-8555, Japan; gotoh.toshiyuki@nitech.ac.jp, izumi@gfd-dennou.org).

Spectrum of passive scalar variance in decaying and steady turbulence is numerically\studied for Schmidt number up to 1000. A new direct numerical simulation (DNS) code has been developed for this purpose, which uses the spectral method for the velocity and the combined compact finite difference method for the scalar. Since there is scale separation between the velocity and scalar fields, the dual grids that are coarse grid foe the velocity and fine grid for the scalar are introduced. The inertial convective range scaling of the spectrum k^{-1} is confirmed and the Batchelor constant is found to be $C_B = 5.57$, and the scalar spectrum in the far diffusive range is of the exponential. On the other hand, Batchelor's, and the Lagrangian spectral theories for the scalar spectrum predict the Gaussian decay in the range, while Kraichnan's model predicts the exponential decay. In order to explain of the differences, intermittency of the straining motion acting on the scalar is introduced through the probability density function (PDF) of the eigenvalue of the rate of strain tensor. The Batchelor spectrum for a given eigenvalue of the rate of strain tensor is averaged over an assumed distribution of the eigenvalue, and compared with the DNS data. It is found that the agreement is very satisfactory. Relations among three theories and intermittency are argued with the emphasis on the spectral shape in the far diffusive range.

Multiscale Statistics of Trajectories with Applications to Football Players and Particles in Fluid Turbulence, **KAI SCHNEIDER[1]*, BENJAMIN KADOCH[2], and WOUTER BOS[3]** ([1]Institut de Mathématiques de Marseille, I2M-CNRS, Aix-Marseille Université, 39 rue Joliot-Curie, 13453 Marseille Cedex 13, France, kai.schneider@univ-amu.fr; [2] IUSTI-CNRS, Aix-Marseille Université, Marseille, France, benjamin.kadoch@univ-amu.fr; [3] LMFA-CNRS Ecole Centrale de Lyon, Université de Lyon, Ecully, France, wouter.bos@ec-lyon.fr)**.**

The angle between two subsequent particle displacement increments is evaluated as a function of the time lag. The directional change of particles can thus be quantified at different scales and multiscale statistics can be performed. Flow dependent and geometry dependent features can be distinguished. The mean angle satisfies scaling behaviors for short time lags based on the smoothness of the trajectories. For intermediate time lags a power law behavior can be observed for some turbulent flows, which can be related to Kolmogorov scaling. The long time behavior depends on the confinement geometry of the flow. We show that the shape of the probability distribution function of the directional change can be well described by a Fischer distribution. Results for two-dimensional (direct and inverse cascade) and three-dimensional turbulence with and without confinement, also including inertial particles with Stokes drag illustrate the properties of the proposed multiscale statistics. The presented Monte-Carlo simulations allow disentangling geometry dependent and flowing independent features. Finally, we also analyze trajectories of football players, which are, in general, not randomly spaced on a field.

Ref.: B. Kadoch, W.J.T. Bos and K. Schneider. Directional change of fluid particles in two-dimensional turbulence and of football players. *Phys. Rev. Fluids*, 2017, under revision. B. Kadoch, M. Bassenne, M. Esmaily-Moghadam, K. Schneider, M. Farge and W. J. T. Bos. Multi-scale geometrical Lagrangian statistics: Extensions and applications to particle-laden turbulent flows. *Proceedings of the 2016 Sumer Program, Center for Turbulence Research,* 53-63, 2016. W.J.T. Bos, B. Kadoch and K. Schneider. Angular statistics of Lagrangian trajectories in turbulence. *Phys. Rev. Lett.*, 114, 214502, 2015.

Scale Similarity of the Particle Clustering in the Inertial range of Turbulence, **TAKETO ARIKI[1], KYO YOSHIDA[2], KEIGO MATSUDA[3], and KATSUNORI YOSHIMATSU[1]** ([1]Institute for Materials and Systems for Sustainability, Nagoya University, Furo-cho, Chikusa ward, Nagoya 464-8601, Japan, ariki@fluid.cse.nagoya-u.ac.jp, yoshimatsu@fluid.cse.nagoya-u.ac.jp; [2]Institute of Physics, Faculty of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennoudai, Tsukuba 305-8571, Ibaraki, Japan, yoshida.kyo.fu@u.tsukuba.ac.jp; [3]Center for Earth Information Science and Technology, Japan Agency for Marine-Earth Science and Technology, Yokohama 236-0001, Japan, k.matsuda@jamstec.go.jp)**.**

Scale-similar behavior of inertial particle is discovered within the inertial sub-range of homogeneous isotropic turbulence. On the basis of the Eulerian approach, the pair-correlation function (PCF) in the inertial range is investigated, where the power law behavior of PCF is discovered from both dimensional and theoretical analysis. Dynamical model for the PCF is derived on the basis of the Lagrangian-renormalized approximation (LRA), whose equilibrium solution well agrees with DNS data. LRA model reveals the existence of the number-density flux from larger to smaller scale, which is driven by the turbulence mixing. The power-law range is exactly expressed from the balance between turbulence mixing and the preferential concentration.

Enhancement of Cloud Radar Reflectivity Factor Due to Turbulent Clustering of Settling Water Droplets, **KEIGO MATSUDA*, RYO ONISHI, and KEIKO TAKAHASHI** (Center for Earth Information Science and Technology, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, 236-0001, Japan, k.matsuda@jamstec.go.jp, onishi.ryo@jamstec.go.jp, takahasi@jamstec.go.jp)**.**

Microscale turbulent clustering of cloud droplets is considered to cause enhancement of cloud radar reflectivity factor. We thus investigate the quantitative influence of turbulent droplet clustering on radar reflectivity factor by using the direct numerical simulation (DNS) of particle-laden isotropic turbulence. The increment of the radar reflectivity factor is evaluated based on the mechanism of particulate Bragg scattering, in which the increment of the factor is proportional to the power spectrum of droplet number density fluctuations. Firstly, we investigate the cases where gravitational droplet settling is negligibly small. The results show that the shape of obtained power spectrum is strongly dependent on the Stokes number, St. Quantitative estimate of the radar reflectivity factor for an idealized cloud scenario reveals that turbulent clustering can cause significant increase of the factor up to 14 dB for typical cloud droplet sizes. Secondly, we investigate the influence of gravitational settling of droplets. The gravitational settling modulates the spatial structure of clustering, and the modulation becomes more significant for larger settling velocity. The settling influence on the power spectrum is also strongly dependent on St. Settling weakens the intensity of clustering at large wavenumbers for St $\leq$ 1, whereas it enlarges the intensity for St > 1. We finally propose an empirical model of the power spectrum for turbulent clustering droplets. Possible errors of radar observation due to the microscale turbulent clustering can be estimated by the proposed model.

Settling of (Non-)Heavy Inertial Particles in Turbulence, **HERMAN J.H. CLERCX***, **MICHEL A.T. VAN HINSBERG** , and **FEDERICO TOSCHI** (Department of Applied Physics, Eindhoven University of Technology, PO Box 513, 5600MB, Eindhoven, The Netherlands; h.j.h.clercx@tue.nl)**.**

In this contribution we will address two aspects of settling processes of small inertial particles in turbulent flows. First we address the role of the pressure gradient and the Basset history force on settling non-heavy particles in homogenous isotropic turbulence. Subsequently we will focus on heavy particles in homogeneous shear turbulence and discuss the phenomenon of symmetry breaking of horizontal drift of the settling particles. The Stokes drag force and the gravity force are usually sufficient to describe the behavior of heavy particles in turbulence, in particular when the particle-to-fluid density ratio R is very large, R=O(1000) or larger. This is in general not the case for smaller particle-to-fluid density ratios, in particular not for R=O(100) or smaller. In that case the pressure gradient force, added mass effects and the Basset history force also play an important role. In the first part of this contribution we focus on the understanding of the role of these additional forces, all of hydrodynamic origin, on the settling of particles in turbulence. In general we found that the pressure gradient force leads to a decrease in the settling velocity. This can be qualitatively understood by the fact that this force prevents the particles from sweeping out of vortices, a mechanism known as preferential sweeping which causes enhanced settling. Additionally, we found that the Basset history force can both increase and decrease the enhanced settling, depending on the particle Stokes number. The influence of shear on the gravitational settling of heavy inertial particles in homogeneous shear turbulence (HST) is remarkable. In addition to the well-known enhanced settling velocity, observed for heavy inertial particles in homogeneous isotropic turbulence (HIT), a horizontal drift velocity is also observed in the shearing direction due to the presence of a nonzero mean vorticity (introducing symmetry breaking due to the mean shear). This drift velocity is the result of the combination of shear, gravity, and turbulence, and all three of these elements are needed for this effect to occur. We extend the mechanism responsible for the enhanced settling velocity

in HIT to the case of HST. Two separate regimes are observed, characterized by positive or negative drift velocity, depending on the particle settling velocity and these regimes will briefly be discussed during this contribution.