4th International Workshop on Cloud Turbulence (online) , March 9-11, 2022, NITech, Nagoya, Japan

JST	Chair	March 9	
13:10-13:20	Watanabe	Gotoh Toshiyuki	Opening
13:20-13:40		Shaw Raymond	Relative roles of mean and fluctuating supersaturation in cloud formation
13:40-14:00		Tajiri Takuya	MRI adiabatic-expansion-type cloud chamber experiments: CCN and INP abilities of atmospheric aerosol particles measured at Tsukuba, Japan
14:00-14:20		Yang Fan	Comparison of large-eddy simulations of a convection cloud chamber using various microphysics and advection schemes
14:20-14:40		Krueger Steven	Supersaturation variability in clouds and in the Pi Chamber
14:40-14:45	Break		
14:45-15:05	Krueger	Grabowski Wojciech	Impact of turbulence on CCN activation and early growth of cloud droplets
15:05-15:25		Chen Sisi	Understanding cloud-aerosol-turbulence interactions in warm and mixed-phase clouds: DNS approach and application
15:25-15:45		Kumar Bipin	Direct numerical simulations of CCN activation: response to particle characteristics
15:45-16:05		Hoffmann Fabian	The importance of small-scale dynamical processes for aerosol-cloud interactions
16:05-16:10	Break		
16:10-16:30	Xu	Bagheri Gholamhossein	The Max Planck CloudKite (MPCK): airborne measurement of cloud microphysics and turbulence
16:30-16:50		Molacek Jan	In situ measurements of cloud droplet clustering at Zugspitze
16:50-17:10			Discussion
JST	March 10		
13:00-13:20	Gotoh	Sreenivasan Katepalli Raju	Special lecture Three comments (loosely) related to clouds
13:20-13:40			
13:40-14:00		Yeung, P.K.	Stokes point-particle dynamics: small-scale turbulence structure and contrast between forward and backward dispersion
14:00-14:20		Ishihara Takashi	DNS data analysis of the collision processes of inertial particles in high Reynolds number turbulence
14:20-14:40		Kobayashi Hiromichi	A Langevin model for gradients of passive scalar in isotropic turbulence
14:40-14:45	Break		
14:45-15:05	Meiburg	Xu Haitao	Experimental study of droplet motion in a plane traveling wave
15:05-15:25		Tsuji Yoshiyuki	Small particles motions in super fluid turbulence
15:25-15:45		Watanabe Takeshi	On the behavior of microbubbles in isotropic turbulence
15:45-16:05		Gorokhovski Mikhael	``Intuitive" models of a droplet in the under-resolved turbulence: breakup, dispersion and evaporation.
16:05-16:10	Break		
16:10-16:30	Gorokhovski	Pumir Alain	Settling and collision of ice crystals in turbulent clouds
16:30-16:50		Meiburg Eckart	Aggregation of cohesive particles in homogeneous isotropic turbulence
16:50-17:10			Discussion
JST	March 11		
13:00-13:20	Ishihara	Onishi Ryo	Microscopic simulations of cloud particle growth
13:20-13:40		Chandrakar Kamal Kant	Supersaturation variability from scalar mixing: evaluation of a new subgrid-scale model using direct numerical simulations of turbulent Rayleigh–Bénard convection
13:40-14:00		Lu Chunsong	Interactions between entrainment-mixing mechanisms and cloud droplet spectral width
14:00-14:20		Yin Chongzhi	Simulation of drizzling marine stratocumulus using the super-droplet method: numerical convergence and comparison to a double-moment bulk scheme
14:20-14:40		Shima Shin-Ichiro	Three-dimensional simulation of a cumulonimbus using the super-droplet method: first preliminary results
14:40-14:45	Break		
14:45-15:05	Shima	Rosa Bogdan	Numerical modeling of dispersed turbulent flows considering particle-scale interactions
15:05-15:25		Arabas Sylwester	Supercooling super-droplets: on particle-based modelling of immersion freezing
15:25-15:45		Schumacher Jőrg	Extreme vorticity events in turbulent Rayleigh-Bénard convection from stereoscopic particle image velocimetry and recurrent neural networks
15:45-16:05		Bodenschatz Eberhard	Cloud microphysics metrology applied to human drops and aerosols
16:05-16:25		Gotoh Toshiyuki	Statistical properties of supersaturation fluctuations in cloud turbulence
16:25-16:45			Discussion and Closing

Time Table of Workshop (20 min =15 +5)

Time is in Japan Standard Time

JST	March 9	JST	March 10	JST	March 11
13:10-13:20	Opening	13:00-13:20	Sreenivasan, K.R.	13:00-13:20	Onishi, R.
13:20-13:40	Shaw, R.	13:20-13:40		13:20-13:40	Chandrakar, K.K.
13:40-14:00	Tajiri,T.	13:40-14:00	Yeung, P.K.	13:40-14:00	Lu, C.
14:00-14:20	Yang, F.	14:00-14:20	Ishihara, T.	14:00-14:20	Yin, C.
14:20-14:40	Krueger, S.	14:20-14:40	Kobayashi, H.	14:20-14:40	Shima, S.
14:40-14:45	Break	14:40-14:45	Break	14:40-14:45	Break
14:45-15:05	Grabowski, W.	14:45-15:05	Xu, H.	14:45-15:05	Rosa, B.
15:05-15:25	Chen, S.	15:05-15:25	Tsuji, Y.	15:05-15:25	Arabas, S.
15:25-15:45	Kumar, B.	15:25-15:45	Watanabe, T.	15:25-15:45	Schumacher, J.
15:45-16:05	Hoffmann, F.	15:45-16:05	Gorokhovski, M.	15:45-16:05	Bodenschatz, E.
16:05-16:10	Break	16:05-16:10	Break	16:05-16:25	Gotoh. T.
16:10-16:30	Bagheri, G.	16:10-16:30	Pumir, A.	16:25-16:45	Discussion and Closing
16:30-16:50	Molacek, J.	16:30-16:50	Meiburg, E.		
16:50-17:10	Discussion	16:50-17:10	Discussion		

Japan (JST)	China（CST）	India (IST)	EU (CET)	USA（EST）	USA（MST）	USA（PST）
13:00-17:00	12:00-16:00	09:30-13:30	5:00-9:00	23:00-03:00	21:00-01:00	20:00-24:00

March 9

Relative roles of mean and fluctuating supersaturation in cloud formation

Abu Sayeed Md Shawon, Prasanth Prabhakaran, Will Cantrell, Raymond A. Shaw

Aerosol-cloud interactions are a primary source of uncertainty in the global properties of clouds and their response to human influences. Aerosol particles become cloud droplets, or activate, when the water vapor supersaturation exceeds a threshold, which depends on the particle's size and chemical composition. In the traditional formulation of the process, only average, uniform supersaturations are considered. However, turbulent environments like clouds intrinsically have fluctuations around mean values in the scalar fields of temperature and water vapor concentration, which determine the supersaturation. Through laboratory measurements and theory, we show that these fluctuations can strongly influence cloud formation through activation. Our results show, even for single-sized, chemically homogeneous aerosols, that fluctuations blur the correspondence between activation and a particle's size and chemical composition and that turbulence can increase the fraction of aerosol particles which activate. The results demonstrate that limiting regimes of mean-dominated versus fluctuation-dominated aerosol activation exist, similar to the well-known aerosol-limited and updraft-limited regimes from adiabatic parcel theory.

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MRI adiabatic-expansion-type cloud chamber experiments: CCN and INP abilities of atmospheric aerosol particles measured at Tsukuba, Japan

Takuya Tajiri, Narihiro Orikasa, Yuji Zaizen, Wei-Chen Kuo, Masataka Murakami

Cloud simulation chamber was built at the Meteorological Research Institute (MRI) to investigate the details of fundamental processes of cloud formation [1]. Aerosol particles determine aspects of inside cloud and affect precipitation forecast through precipitation efficiency. For a better understanding of the aerosol effects on clouds, it is crucially important to reveal the relationship between the physico-chemical properties of aerosol, such as dry particle size distribution, cloud condensation nuclei (CCN) and ice nucleating particles (INP) abilities.

MRI's cloud chamber has been used to investigate the ability of surrogates of atmospheric mineral dusts [1, 2], biological materials [3] and metal oxides to act as INPs [4], and to inquire the optimal characteristics of hygroscopic and glaciogenic seeding materials to act as CCN and INPs, along with their effects on the initial microphysical structures of clouds so far. We also have been conducted multi-year ground-based continuous observation of atmospheric aerosols since March 2012 on the MRI campus in Tsukuba by using CCN counter, MRI's IN counter and aerosol instruments [5].

INP number concentrations were usually very low compared to the CCN number concentrations, while the existence of various types of aerosol particles in terms of their concentrations, size distributions and chemical compositions including the externally/internally mixed state has been identified. In this talk, the possibility of atmospheric aerosol particles to act as efficient CCN and INPs and their role in natural cloud formation processes will be discussed.

References

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Comparison of large-eddy simulations of a convection cloud chamber using various microphysics and advection schemes

Fan Yang

Bin microphysics schemes are useful tools for cloud simulations and are often considered as providing benchmarks but may experience issues with numerical diffusion. In addition, the transport of hydrometors in space depends on the choice of advection schemes which can also change cloud simulation results, making it challenging to isolate and quantify the role of microphysics schemes. A convection cloud chamber at Michigan Technological University has shown to be an optimal laboratory environment to study aerosol-cloud-turbulence interactions. In this study, an atmospheric large-eddy simulation model is adapted to simulate a statistically steady-state cloud in MTU convection cloud chamber under well-constrained and observationally guided conditions. Two bin microphysics schemes for the transport of microphysical variables are employed for model intercomparison. Results show that simulated clouds in a convection chamber can differ considerably by choosing different combinations of microphysics and advection schemes. The variations among cases are not sensitive to changes in aerosol injection rates. These simulation comparisons using different microphysics and advection schemes help understand the uncertainties of cloud chamber simulations.

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Supersaturation variability in clouds and in the Pi Chamber

Steven Krueger

It is well known that entrainment is a significant source of supersaturation variability in cumulus and stratocumulus clouds. However, the effects of supersaturation variability on droplet size distributions (DSDs) remains challenging to represent in models, even in direct numerical simulation (DNS) models, due to the tremendous range of spatial scales involved. Detailed measurements in cloudy Rayleigh-Benard convection in the Michigan Technological Universoty's Pi Chamber suggest that supersaturation variability is significant, and thus is expected to affect the measured DSDs. Numerical modeling studies of moist (no droplets) and cloudy Rayleigh-Benard convection without side walls produce less supersaturation variability than is observed in the PI Chamber. This suggests that the (non-adiabatic) side walls contribute to the supersaturation variability in the Pi Chamber, and may produce it in a way that is analogous to production of supersaturation variability by entrainment in cumulus clouds. We are exploring this idea with the Explicit Mixing Parcel Model (EMPM), a model that depicts the fine-scale internal structure of a cloud using a 1D domain up to several hundred meters in extent. The cloud structure evolves in the EMPM as a consequence of a sequence of discrete entrainment events and an explicit representation of turbulent mixing based on Kerstein's (1988) linear eddy model. The EMPM includes the activation and condensational growth of individual droplets

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Impact of turbulence on CCN activation and early growth of cloud droplets

Wojciech W. Grabowski, Lois Thomas, Bipin Kumar

Scaled-up DNS and implicit LES simulations are used to study turbulent cloud base CCN activation and early growth of cloud droplets. The simulation framework includes a triply periodic computational domain 1,000 cubic meters filled with inertial-range homogeneous isotropic turbulence. The domain experiences decrease of the mean air temperature and reduction of the mean pressure, both mimicking the rise of an adiabatic air parcel through the cloud base. Results of turbulent simulations are compared to CCN activation and droplet growth within a classical nonturbulent rising parcel. The key difference is a blurriness of the separation between activated and nonactivated (haze) CCN, especially for weak mean ascent rates, when CCN activate and subsequently some deactivate instead of becoming cloud droplets above the cloud base. This leads to significantly larger spectral widths in turbulent parcel simulations compared to the adiabatic nonturbulent parcel once CCN activation is completed. Further increase of the spectral width in the turbulent parcel is similar to that for the initially-monodisperse droplets in the inertial-range homogeneous isotropic turbulence, with the standard deviation of the radius squared increasing approximately as the square root of time. This contrasts with the classical nonturbulent parcel framework for which the radius squared standard deviation above the cloud base remains constant.

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Understanding cloud-aerosol-turbulence interactions in warm and mixed-phase clouds: DNS approach and application

Sisi Chen, Lulin Xue, Wojciech Grabowski, Anders Jensen, Sarah Tessendorf, Roy Rasmussen

Accurate representation of warm and mixed-phase microphysics in numerical models is critical for the prediction of physical processes in clouds such as cloud electrification, the phase transformation of mixed-phase clouds, and precipitation in the mesoscale models. The key to improving the microphysical representation is to gain a process-level and quantitative understanding of those processes at scales that are crucial to particle-particle interactions and particle-flow interactions. Therefore, the Lagrangian-particle-based DNS that resolves those scales becomes a favorable tool to serve this purpose.

In the first part of this talk, I will present our recent study on the impacts of giant aerosol particles on the evolution of cloud droplet size distributions and how small-scale turbulence affects supersaturation and spectral broadening. Even though the DNS has been widely used to study warm microphysics, few have been used to study the mixed-phase processes. To address this, we implemented the diffusional growth of the ice crystals into the DNS to study the interactions between droplets and ice in a turbulent environment. In the second part, I will present the results of this newly developed model and explore the ice growth in the turbulent, mixed-phase environment.

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Direct numerical simulations of CCN activation: response to particle characteristics

Lois Thomas, Bipin Kumar, Andreas Zuend

DNS of a particle-laden (CCN and cloud droplets) air volume of homogenous isotropic turbulence ascending in the atmosphere was conducted to study aerosol activation physics. The main focus of this study is the investigation of the impact of turbulence fluctuations on the CCN activation in contrasting scenarios. In the first part, we investigate the activation of single-salt CCN using mono-disperse and normal distributions. In the (initially) mono-disperse case, the maximum activation is not achieved in a single step, depicting the importance of turbulent fluctuations while for the normal distribution, the activation occurs according to particle size. Bi-modal lognormal distributions of mixed organic-inorganic CCN are considered in contrasting scenarios in the second part of the study where the compositions and effective hygroscopicities of the CCN are decided based on the volume ratio of the individual components. Polluted and pristine distributions and corresponding activation properties in a turbulent rising parcel are examined and the pristine environment produced larger supersaturation values, larger fluctuations and larger mean sizes. We also examine the CCN activities in organic or inorganic-rich particles. DNS results agree with our understanding of CCN activation and cloud droplet growth and provide some insight into the impact of turbulent fluctuations, particle characteristics, and environmental conditions on the activation process.

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The importance of small-scale dynamical processes for aerosol-cloud interactions

Fabian Hoffmann

The radiative forcing from aerosol-cloud interactions can be attributed to the Twomey effect, which explains higher cloud albedos in response to an increase in the droplet concentration, and liquid water adjustments. Traditionally, liquid water adjustments have been equated with the Albrecht effect, the inhibition of precipitation due to smaller droplets in aerosol-laden conditions, which can be responsible for a larger cloud water content and hence cloud albedo. More recently, cloud microphysical effects on the entrainment rate gained increasing interest. By modulating the mixing of clouds with their environment, aerosol-cloud interactions can significantly influence the cloud water and cloud albedo, with the potential to completely offset the Twomey effect.

The physical processes modulating entrainment by aerosol-cloud interactions are based on droplet size and number dependent sedimentation and evaporation, and are understood conceptionally well. The quantitative understanding of these processes is, however, limited. The main reason for this are the high requirements on the model resolution to represent the smallest scales on which cloud microphysics interact with the dynamics of the entrainment process. In this talk, we will discuss approaches for investigating these processes explicitly, and address the importance of microphysical effects on the entrainment rate in aerosol-cloud interactions, before concluding the talk by highlighting their importance in assessing potential geoengineering (marine cloud brightening) endeavors.

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The Max Planck CloudKite (MPCK): airborne measurement of cloud microphysics and turbulence

Gholamhossein (Mohsen) Bagheri

Unresolved processes in clouds, such as moist convection and cloud formation, are the main source of uncertainty in weather and climate models. While remote sensing techniques have provided tremendous information on cloud processes at scales greater than a few meters, smaller scales are the least explored. At small scales, the interactions between fine-scale turbulence and clouds determine the evolution of the droplet size distribution, and thus the possibility of rain formation and cloud albedo. To this end, we have developed the Max Planck CloudKite (MPCK) platforms for the in-situ study of cloud microphysics and turbulence from dissipative to energy-injecting scales. The MPCK consists of a helium-filled tethered balloon/kite that can carry the specially designed instrument boxes up to 1.5 km above the ground. We have developed two instrument boxes, namely (i) the MPCK+, which consists of high-resolution imaging instruments (collocated particle image velocimetry and holography) to study fine-scale features of clouds, and (ii) the mini-MPCK, which consists of multiple anemometers, hot wires, and droplet sizing instruments and can operate continuously for more than 15 hours. I will present the preliminary results obtained with the MPCKs during the EUREC4A field campaign (http://eurec4a.eu), where we collected about 210 hours of data from shallow cumulus clouds over the Atlantic Ocean aboard the German research vessels Maria S. Merian and Meteor.

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In situ measurements of cloud droplet clustering at Zugspitze

Jan Moláček, Guus Bertens, Gholamhossein Bagheri, Eberhard Bodenschatz

The growth of cloud droplets across the diameter range of 15 to 50 micrometers is thought to be dominated by the collision-coalescence process. As such, it is sensitively dependent on the turbulence statistics and droplet size distribution. In order to make quantitative predictions of the growth rate, these variables are often divided into the droplet spatial distribution, size distribution and relative velocity distribution.

Here we focus on the spatial distribution, encapsulated by the radial distribution function (RDF), and its behaviour at small separations, which is of the highest relevance to the collision rate. While numerical and theoretical results have been around for some time [1-3], their applicability is limited due to omission of some potentially important factors such as droplet charge or hydrodynamic interaction between droplets. Therefore, experimental measurements are invaluable as means of determining the validity of using these results for practical purposes such as weather prediction.

We present the results of our in situ measurements performed at the environmental research station Schneefernerhaus near the peak of Mt. Zugspitze in the german Alps. We have developed a particle tracking setup [4] capable of measuring simultaneously the position, velocity and diameter of cloud droplets within a measurement volume of about 15 cm3. We describe the specific challenges the hostile and changeable mountain weather poses in comparison to a typical laboratory setup, and how we have solved these challenges. We discuss the fundamental limits of particle tracking using high-speed cameras when it comes to extracting the radial distribution function at small separations. Finally, we compare our RDF results to those of other experiments and numerical simulations.

References

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March 10

Special lecture
Three comments (loosely) related to clouds

Katepalli Raju Sreenivasan

The concentration of cloud droplets with radii in the range of 5 to 10 microns, as well as aerosols, can be regarded as passive scalars with very low diffusivities (or high Schmidt numbers, Sc). Cloud physicists thus have a natural interest in the dynamics of mixing at high Sc. Even though several details remain to be understood, a good part of the problem seems to be amenable to a logical development; one such will be attempted in this talk, which will discuss our current knowledge of the subject, in part based on the author ' s work done over the years in collaboration with Dhawal Buaria, Diego Donzis, Kartik Iyer, Joerg Schumacher, and P.K. Yeung, and in part taking inspiration from other independent simulations of others such as Toshyuki Gotoh, Takeshi Watanabe, Izumi Saito and others in Japan.

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Stokes point-particle dynamics: small-scale turbulence structure and contrast between forward and backward dispersion

P. K. Yeung

Numerical simulation and (stochastic) closure modeling for the dynamics of inertial point particles in turbulence present many challenges beyond those encountered in Lagrangian fluid particle motion, even in regimes where the effects of finite particle size and two-way coupling may be considered small. In this talk we examine a few fundamental aspects using direct numerical simulations of stationary isotropic turbulence at different Reynolds numbers. The Stokes number (defined as ratio of particle momentum response time to the Kolmogorov time scale) is varied from very small to very large. Datasets examined include the fluid velocity and velocity gradients (hence dissipation rate and enstrophy, which are highly intermittent) evaluated along the Stokes particle trajectories. The strong contrast between forward and backward dispersion of inertial particle pairs is addressed through particle displacements and time histories of fluid velocity gradients along the particle trajectories. We also discuss briefly some aspects concerning numerical and algorithmic aspects that arise in particle tracking at particle counts exceeding 1 billion.

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DNS data analysis of the collision processes of inertial particles in high Reynolds number turbulence

Takashi Ishihara, Hiroki Morinaka, Mizuki Asai, Yoshiki Sakurai

Collision processes of inertial particles in high Reynolds number turbulence are investigated by tracking 2048^3 particles for each of eight different Stokes numbers in direct numerical simulations (DNSs) of turbulence with 4096^3 grid points. Here the Stokes number is the ratio of particle relaxation time to the Kolmogorov timescale. DNS data analysis of the particles and the turbulent field shows that large-scale significant vortical clusters exclude particles with large inertia, make high density regions of the particles near the vortical clusters and enhance particle collisions. The results of DNS data analysis of the effect of gravity acting to the inertial particles will be also reported.

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A Lagrangian method for direct numerical simulation of scalar turbulence at high Reynolds and Schmidt numbers

Izumi Saito, Takeshi Watanabe, Toshiyuki Gotoh

We develop a new method for direct numerical simulation (DNS) of scalar turbulence at high Reynolds and Schmidt numbers. This method is Lagrangian, which calculates the motion of particles in turbulence and analyses statistical properties of scalar fields of particles, such as particle number, mass, and temperature. The theoretical base of the method is a convergence property shown by a previous study, where the variance spectrum of the temperature field of particles approaches, in the limit of large particle thermal response time (τ_θ), to the spectrum for infinite Schmidt number, ie. the Batchelor spectrum. This method is fee from requirements for resolution and stability of scalar fields, making it possible to realize scalar turbulence at high Reynolds number as well as high Schmidt number with relatively reasonable computational cost. For verification, we conducted DNSs of turbulence with particles with various τ_θ, and confirmed that the variance spectrum converges to the Batchelor spectrum for larger τ_θ and that the Batchelor constant is estimated as $C_B \sim 5.7$. We also provide the results of the large-scale DNS with Taylor micro-scale Reynolds number Re_λ up to 570.

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A Langevin model for gradients of passive scalar in isotropic turbulence

Hiromichi Kobayashi, Toshiyuki Gotoh, Hideaki Miura

We present results of Langevin model for gradients of a passive scalar with or without phase relaxation time in isotropic turbulence. We adopted the concept of the recent deformation of the Gaussian field proposed by Johnson and Meneveau (2016). The PDF result of velocity gradient is the same as that by Johnson and Meneveau (2016). Our goal is to use the results for constructing the two-way coupled LES model using the gradients of velocity and passive scalar. We will discuss effects of the Schmidt number and Damköhler number on the PDFs of scalar gradient.

Johnson, P. L., Meneveau, C. ”A closure for Lagrangian velocity gradient evolution in turbulence using recent deformation mapping of initially gaussian-fields,” Journal of Fluid Mechanics, vol. 804 pp. 387-419 (2016)

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Experimental study of droplet motion in a plane traveling wave

Dongmei Wan, Haitao Xu

Dynamics of particles in an unsteady flow is an essential part for the understanding of cloud turbulence interaction. Here we report an experimental investigation of droplet dynamics in a plane traveling wave, one of the simplest unsteady flow. The traveling wave in a straight channel was generated by modulating the phases and amplitudes of two speakers installed at the two ends of the channel, and was verified by measurements of the instantaneous pressures along the tunnel and by particle image velocimetry (PIV) measurements of the air flow in the channel. Droplets were then injected into the flow and their motion under the sound wave was recorded by a high-speed camera. The air flow around the particle was simultaneously measured by PIV, from which we measured the ratio of the velocity amplitudes of the droplet and the air, and the phase differences between the two. Over the range of sound frequencies and sound pressures covered by the experiments, The theoretical solution from the wave equation approach gives the same results as the experiments and the unsteady Tsai-Maxey-Riley-Gatignol equation with the history forces. Our experimental results show that even for droplets in air, the history forces still play a non-negligible role, especially for the phase difference between the droplet motion and the air motion.

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Small particles motions in super fluid turbulence

Yoshiyuki Tsuji

In this study, we use the PTV (Particle Tracking Velocimetry) to analyze the Lagrange trajectories of small particles in superfluid helium from a statistical point of view. The particle trajectories are divided into superfluid components and normal fluid components based on our original definition and are further investigated to clarify the effects of quantum vortices and bath temperature on their motions. Quantum vortex density evaluated by the particle trajectory is compared with the ones obtained by sound attenuation method.

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On the behavior of microbubbles in isotropic turbulence

Hiroya Hamazaki, Takeshi Watanabe, Izumi Saito, Toshiyuki Gotoh

Behavior of the microbubbles in three-dimensional homogenous isotropic turbulence is investigated by conducting the direct numerical simulations. When the Stokes number of the bubbles defined using Kolmogorov time takes a value near unity, the spatial distribution of most of the microbubbles tends to be localized near the vortex structure (Mazzitelli et al (2003)). On the other hand, accumulation of microbubbles is also observed in places where the intensity of vorticity is very small. In order to investigate this in detail, we analyze the spatial distribution of bubbles using a frozen turbulent field. It is shown that the bubbles are localized even in places where the vortex structures are not observed. Difference in the distribution of bubbles between the Stokes law and the Schiller-Naumann law using for the drag force acting on bubbles is examined. As a result, it is found that there are no significant differences in the behavior of bubbles when the effective dimensionless time is the same.

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“Intuitive” models of a droplet in the under-resolved turbulence: breakup, dispersion and evaporation.

Mikhael Gorokhovski

Measurements (by Siebert et al.) and three Annual Reviews of Fluid Mechanics (Shaw, Grabowski & Wang and Mellado) highlighted an essential feature of turbulence in stratocumulus clouds: the high Reynolds number and the wide inertial subrange of scales, the low rate of overall dissipation and strong intermittency on small turbulent scales. The latter is manifested by intense fluctuations of the velocity gradients, as a signature of stretched long-lived flow structures generated in narrow regions. This may have a strong impact on droplets formation, dynamics and evaporation. However, in LES the microscale turbulent properties are under-resolved. In this talk we will discuss how in the form of stochastic models the intermittency effects may be introduced for simulations of droplets breakup, motion and evaporation on residual highly intermittent scales. To this end the key-characteristics of considered models are linked to vortical flow structures, and the main emphasis in formulation of these models is to be coherent with the recent knowledge on the acceleration of fluid particles “seen” by a droplet along its trajectory. The analysis is supported by DNS and practical LES.

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Settling and collision of ice crystals in turbulent clouds

Alain Pumir, Aurore Naso, Md. Zubair Sheikh, Emmanuel Leveque, Bernhard Mehlig, Kristian Gustavsson

Small non-spherical ice crystals in clouds settle through a turbulent fluid. As they settle, they can orient themselves, which in turn affects radiation reflection. They can also collide with each other, which leads to aggregation, and to the formation of larger size particles (such as grauples). I will present the results of a theoretical and numerical study of the problem. The first issue I will discuss concerns the forces and torques acting on small crystals as they move through the fluid, and in particular the importance of fluid inertia to orient the crystals. The dependence of the orientation on the geometric properties of the crystals and on the turbulence intensity can be summarized as an elementary phase diagram. Finally, our results concerning the probability of collisions between ice crystals point to several mechanisms that can bring particles together. Aside from the classical effect induced by the turbulent velocity gradient, the difference in settling velocities between crystals with different orientations can significantly contribute to the collision rate, along with the effect of particle inertia (“sling effect”).

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Aggregation of cohesive particles in homogeneous isotropic turbulence

K. Zhao, F. Pomes, B. Vowinckel, T.-J. Hsu, B. Bai, E. Meiburg

We investigate the dynamics of cohesive particles in homogeneous isotropic turbulence, based on one-way coupled simulations that include Stokes drag, lubrication, cohesive and direct contact forces. We observe a transient aggregation phase, followed by a statistically steady equilibrium phase. We analyze the temporal evolution of aggregate size and shape due to aggregation, breakage and deformation. Larger turbulent shear and weaker cohesive forces yield smaller elongated aggregates. Aggregation proceeds most rapidly when the fluid and particle time scales are balanced and a suitably defined Stokes number is O(1). During the transient stage, cohesive forces of intermediate strength produce aggregates of the largest size, as they are strong enough to cause aggregation, but not so strong as to pull the aggregate into a compact shape. Small Stokes numbers and weak turbulence delay the onset of the equilibrium stage. During equilibrium, stronger cohesive forces yield aggregates of larger size. The equilibrium aggregate size distribution exhibits a preferred size that depends on the cohesive number. We observe that aggregates are generally elongated by turbulent stresses before breakage. Aggregates of size close to the Kolmogorov length scale preferentially align themselves with the intermediate strain direction and the vorticity vector. Aggregates of smaller size tend to align themselves with the extensional strain direction. More generally, aggregates are aligned with the strongest Lagrangian stretching direction. The Kolmogorov scale is seen to limit aggregate growth. We propose a new aggregation model with a variable fractal dimension that predicts the temporal evolution of the aggregate size and shape.

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March 11

Microscopic simulations of cloud particle growth

Ryo Onishi, Kota Yanagi, Keisuke Sumitomo, Shintaro Takeuchi, Keigo Matsuda, Dmitry Kolomenskiy

We have been investigating the cloud particle growth in turbulence using an Euler-Lagrangian hybrid method, e.g., the Lagrangian Cloud Simulator (LCS), where the flow is calculated with the Euler method and the particle with the Lagrangian tracking method. Our microscopic simulations revealed the intrinsic statistical fluctuations of macroscopic growth speed of cloud droplets in turbulence (e.g., Onishi et al., 2015). For example, the fluctuations showed a power of -2 with respect to the number of droplets, which is consistent with the binomial distribution theory. However, they were larger than the theory by the unknown factor of 5. We here clarify the source of that factor and by means of ensemble simulations of LCS. We have been also working on further development of LCS so that it can calculate the motion and growth of ice particles with non-spherical shapes. The lubrication force acting on the adjacent particles is relevant for particle collisions. However, the finite grid width prevents the simulations from accurate consideration of the force. We here propose a simple but moderately robust estimation of the lubrication force acting on approaching pair of non-spherical particles. The robustness has been confirmed for an approaching pair of cylinders in a two-dimensional shear flow.

We have implemented the Immersed Solid Method (ISM), one of the immersed boundary methods for size-resolving simulations, in the Lagrangian Cloud Simulator (LCS) [2], which adopts the so-called Euler-Lagrangian framework and can simulate droplet growth in air turbulence. This implementation enables the LCS to deal with large particles whose particle Reynolds numbers (Rep) exceed unity or whose sizes exceed the Kolmogorov scale. Several validation tests for drag coefficient and collision efficiency have been completed. They have shown the robustness of the LCS-ISM and its good computational efficiency. A high-performance computing with the LCS-ISM has successfully obtained turbulent collision statistics of large spherical particles in homogeneous isotropic turbulence. The LCS-ISM simulations, i.e., the size-resolving simulations, has quantified the possible error induced if the point-particle assumption is adopted for large Rep inappropriately. It can be also used to highlight several issues unsolvable if with the point-particle assumption.

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Supersaturation variability from scalar mixing: evaluation of a new subgrid-scale model using direct numerical simulations of turbulent Rayleigh–Bénard convection

Kamal Kant Chandrakar, Hugh Morrison, Wojciech W. Grabowski, George H. Bryan, Raymond A. Shaw

Supersaturation fluctuations in the atmosphere are critical for cloud processes. A nonlinear dependence on two scalars – water vapor and temperature – leads to different behavior than single scalars in turbulent convection. For modeling such multiscalar processes at subgrid-scales (SGS) in large-eddy simulations (LES) or convection-permitting models, a new SGS scheme is implemented in the CM1 LES model that solves equations for SGS water vapor and temperature fluctuations and their covariance. The SGS model is evaluated using benchmark direct-numerical simulations (DNS) of turbulent Rayleigh–Bénard convection with water vapor as in the Michigan Tech Pi Cloud Chamber. This idealized setup allows thorough evaluation of the SGS model without complications from other atmospheric processes. DNS results compare favorably with measurements from the chamber. Results from LES using the new SGS model compare well with DNS, including profiles of water vapor and temperature variances, their covariance, and supersaturation variance. SGS supersaturation fluctuations scale appropriately with changes to the LES grid spacing, with the magnitude of SGS fluctuations decreasing relative to those at the resolved scale as the grid spacing is decreased. Sensitivities of covariance and supersaturation statistics to changes in water vapor flux relative to thermal flux are also investigated by modifying the sidewall conditions. Relative changes in water vapor flux substantially decrease the covariance and increase supersaturation fluctuations even away from boundaries. It has implications for supersaturation fluctuations generated due to entrainment in atmospheric clouds.

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Interactions between entrainment-mixing mechanisms and cloud droplet spectral width

Chunsong Lu, Shi Luo, Yangang Liu, Sinan Gao

Entrainment-mixing processes have significant effects on aerosol-cloud interactions, warm-rain initiation, etc. Quantitative description of homogeneous mixing degree is critical to improve parameterization of entrainment-mixing mechanisms in models. Cloud droplet spectral width affects warm-rain initiation, aerosol indirect effect evaluation, etc. How do the entrainment-mixing mechanisms and cloud droplet spectral width interact with each other?

(1) Effects of cloud droplet spectral width on entrainment-mixing mechanisms
Most studies explicitly or implicitly assume monodisperse initial cloud droplet size distribution (CDSD). The homogeneous mixing degree defined for monodisperse CDSD is not applicable for different initial cloud droplet spectral width. To overcome this weakness, a new homogeneous mixing degree weighted by CDSD is defined based on the Explicit Mixing Parcel Model simulations. This new microphysical measure is verified with dynamical measures.

(2) Effects of entrainment-mixing mechanisms on cloud droplet spectral width
It is not clear how cloud droplet spectral width vary when entrainment-mixing mechanisms change from homogeneous to extreme inhomogeneous. With the Explicit Mixing Parcel Model, it is found that relative dispersion is positively correlated with homogeneous mixing degree, when homogeneous mixing degree is smaller than 50%; when homogeneous mixing degree increases, the correlation becomes negative.

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Simulation of drizzling marine stratocumulus using the super-droplet method: numerical convergence and comparison to a double-moment bulk scheme

Chongzhi Yin, Shin-ichiro Shima, Chunsong Lu, Lulin Xue

Super-droplet Method (SDM) is a Lagrangian particle-based, Monte Carlo stochastic coalescence algorithm developed by Shima et al. (2009). In this method, each super-droplet represents a multiple number of aerosol/cloud /precipitation particles with the same attributes and position. Using the SDM, cloud microphysical processes can be represented more accurately and interactions between clouds and aerosols can be simulated explicitly. In order to find how fine the spatial resolution is required for accurate simulation of marine stratocumulus when using the SDM, a series of simulations based on the DYCOMSII (RF02) setup with different horizontal and vertical grid resolutions are conducted. The results are compared with that of the double-moment bulk scheme of Seiki and Nakajima (2014) (SN14, hereafter) and the model intercomparison project (MIP) results. The horizontal (DX = DY) and vertical grid length (DZ) tested ranges from 12.5 m to 50 m and from 2.5 m to 10 m, respectively. We show that the grid size we tested is not small enough and that the grid convergence is not yet achieved in our SDM and SN14 simulations. For both SDM and SN14, all quantities are getting closer to the true solution as the grid resolution is refined and the numerical convergence properties are more dependent on DZ than DX. A much finer vertical resolution ($DZ \ll 2.5$m) is necessary for almost all quantities in both two schemes. SN14 converges faster than SDM, horizontal resolution of DX=25m is sufficient for all the quantities in SN14, while $DX < 12.5$m is still not sufficient for some quantities in SDM. Numerical convergence of cloud droplet number concentration (CDNC) regarding super-droplet number concentration (SDNC) at different resolutions is also discussed. The result suggests that SDNC as small as 16 super-droplets per grid cell is sufficient when grid resolution is 50 m x 5 m (DX x DZ). In conclusion, SDM results are in agreement with SN14 and MIP results in general. Under the range we tested, the grid convergence is not achieved for both SDM and bulk scheme, but the grid convergence characteristic is consistent with previous studies (Matheou and Teixeira, 2019; Mellado et al., 2018; Pedersen et al., 2016) with isotopic grids (DX/DZ = 1). In addition, CDNC converges when SDNC reaches to 16 per cell at the resolution of 50 m × 5 m. We are now conducting a more detailed quantitative analysis and the results will be also presented.

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Three-dimensional simulation of a cumulonimbus using the super-droplet method: first preliminary results

Shin-ichiro Shima

The super-droplet method (SDM) is a particle-based numerical algorithm that enables accurate cloud microphysics simulation with lower computational demand than multi-dimensional bin schemes. Using the SDM, we developed a detailed numerical model of mixed-phase clouds in which ice morphologies are explicitly predicted without assuming ice categories or mass-dimension relationships (Shima et al., 2020). We are now conducting a 3D large-eddy simulation of a cumulonimbus. In this talk, the first preliminary results will be presented.

Shima, S., Sato, Y., Hashimoto, A., and Misumi, R.: Predicting the morphology of ice particles in deep convection using the super-droplet method: development and evaluation of SCALE-SDM 0.2.5-2.2.0, -2.2.1, and -2.2.2, Geosci. Model Dev., 13, 4107–4157, https://doi.org/10.5194/gmd-13-4107-2020, 2020.

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Numerical modeling of dispersed turbulent flows considering particle-scale interactions

Bogdan Rosa, Ahmad Ababaei, Antoine Michel

Parametrization of cloud microphysical processes in NWP models is viewed as the major source of uncertainty of simulated forecasts. To develop more realistic representations of the sub-grid scale cloud processes a wide range of effects related to both droplet-air and droplet-droplet interactions must be taken into account. In this study we investigate the dynamics of inertial particles in homogeneous isotropic turbulence, under one-way momentum coupling, using an innovative approach that incorporates the effect of long-range many-body aerodynamic interactions along with the short-range lubrication forces. The new implementation couples hybrid direct numerical simulations with the analytical solutions of two rigid spheres moving in an unbounded fluid. The main aim is to examine possible effects of aerodynamic interactions on particle collision statistics, which translates into the collision efficiency. Our results show that for the turbulent kinetic energy dissipation rates typical of atmospheric clouds, the radial relative velocities of the droplets increase, and the radial distribution function decreases in the near-contact region if the lubrication forces are considered. These changes are more pronounced when gravity is considered. The effect of mass loading on the collision statistics is also investigated, demonstrating an increase in the radial relative velocity and a reduction in the radial distribution function with the droplet concentration.

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Supercooling super-droplets: on particle-based modelling of immersion freezing

S. Arabas, J. H. Curtis, I. Silber, A. Fridlind, D.A. Knopf, M. West, N. Riemer

Particle-based models offer an alternative to bulk or bin (sectional) approaches for representing cloud microphysics in frameworks such as large-eddy simulations. The particle-based component of such simulations resolves the dynamics of so-called super-particles, each representing a multiplicity of modelled cloud condensation nuclei (CCN), ice nucleating particles (INP), water drops or ice particles. It is a Monte-Carlo type approach enabling detailed representation of cloud droplet and ice crystal formation and growth, and the coupling of these processes with the budget of ambient aerosol and with the flow dynamics.

In this work, we focus on the representation of the immersion freezing of supercooled droplets, the ice formation process contingent on the presence of insoluble ice formation nuclei within the droplets. We compare two formulations based on the so-called singular and time-dependent approaches, both cast in the framework of probabilistic particle-based simulation. The comparison is carried out using an idealised two-dimensional prescribed-flow framework mimicking a stratiform mixed-phase cloud. We further explore ways of informing the particle-based model with laboratory data from immersion freezing experiments.

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Extreme vorticity events in turbulent Rayleigh-Bénard convection from stereoscopic particle image velocimetry and recurrent neural networks

Valentina Valori, Robert Kräuter, Jörg Schumacher

High-amplitude events of the out-of-plane vorticity component are analyzed by stereoscopic particle image velocimetry in the bulk region of dry turbulent Rayleigh-Bénard convection in air. The Rayleigh numbers Ra vary from 1.7e4 to 5.1e5. The experimental investigation is connected with a comprehensive statistical analysis of long-term time series of the out-of-plane vorticity component and individual velocity derivatives. A statistical convergence for derivative moments up to an order of 6 is demonstrated. Our results are found to agree well with existing high-resolution direct numerical simulation data [1] in the same range of parameters, including the extreme vorticity events which appear in the far exponential tails of the corresponding probability density functions. The transition from a Gaussian to a non-Gaussian statistics of velocity derivatives in the bulk of a convection flow is confirmed experimentally. The experimental data are then also taken to train a recurrent neural network in the form of a reservoir computing model that is able to reproduce highly intermittent experimental time series of the vorticity and thus also to predict extreme out-of-plane vorticity events. In the prediction phase, the trained machine learning model is run with sparsely seeded, continually available measurement data. The dependence of the prediction quality on the sparsity of the partial observations is also documented. Our latter result paves the way to machine–learning–assisted experimental analyses of small-scale turbulence for which time series of missing velocity derivatives can be provided by generative algorithms [2]. In addition, we will discuss in brief possible implications for the cloud microphysics.

[1] V. Valori, J. Schumacher, Europhys. Lett. 134, 34004 (2021).
[2] V. Valori, R. Kräuter, J. Schumacher, arXiv:2112.05442 (2021).

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Cloud microphysics metrology applied to human drops and aerosols

Eberhard Bodenschatz

I will report on the results of a measurement campaign of more than 200 volunteers aged 5-80 on respiratory drops and aerosols from 20nm to millimeters. I shall discuss the results and address open question.

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Statistical properties of supersaturation fluctuations in cloud turbulence

Toshiyuki Gotoh, Izumi Saito, Takeshi Watanabe

Spectrum of the supersaturation in isotropic turbulence is theoretically and numerically examined. The supersaturation is assumed to be excited by the uniform mean gradient of the supersaturation in the vertical direction. It is theoretically shown that the supersaturation spectrum has three power law ranges, two are $k^{-5/3}$ with different amplitudes in the wide enough inertial range, and the other is $k^{-1-2C_B D_K}$ in the viscous-convective range, where C_B is the Batchelor constant and D_K is the Damköhler number that is defined as the ratio of the Kolmogorov time to the phase relaxation time of the supersaturation. The two $k^{-5/3}$ spectra are observed in the shell model for the scalar turbulence for very high Reynolds number. The one point PDF (probability density function) of the supersaturation is also examined in DNS and found to deviate from the Gaussian depending on the Damköhler number.

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