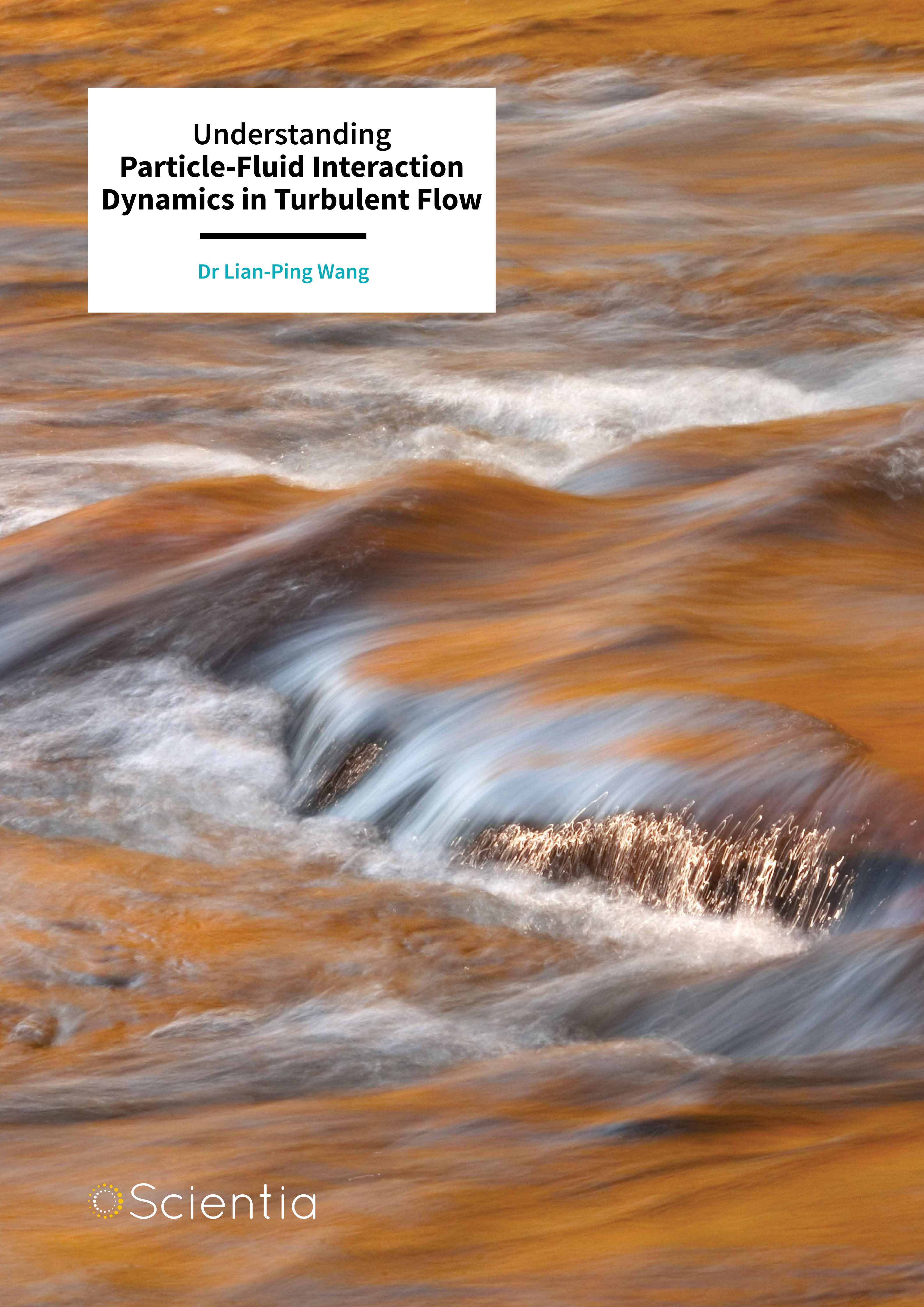


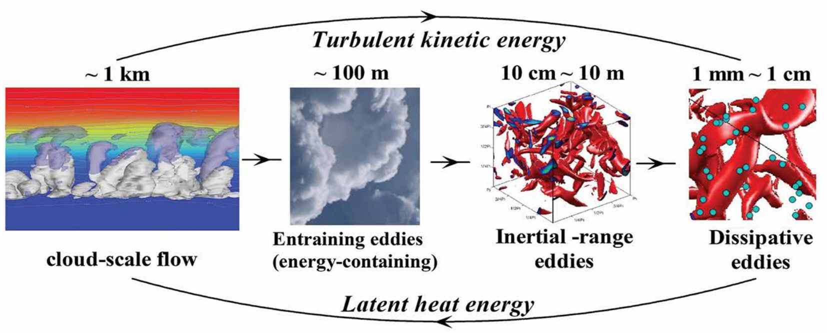
Understanding **Particle-Fluid Interaction Dynamics in Turbulent Flow**

Dr Lian-Ping Wang

Scientia

UNDERSTANDING PARTICLE-FLUID INTERACTION DYNAMICS IN TURBULENT FLOW

Almost every aspect of the global water cycle involves a mixture of fluids and particles – raindrop formation, ocean currents and water percolation through the soil. This mixture of gas and liquid or liquid and solid causes behaviour that is important to understand, but difficult to predict. This is particularly true when turbulent flow occurs. **Dr Lian-Ping Wang** at the University of Delaware has developed models and methods that have greatly improved our ability to understand and predict phenomena from localised rainfall patterns to particle transport in industrial processes.



Multiphase fluid flow occurs when flows contain multiple phases of matter, such as raindrops in air, and river water mixed with sediment. Many environmental processes involve multiphase flow, as do many industrial activities. Multiphase flow, particularly when it is turbulent and complex, is difficult to predict and can present unexpected phenomena. Many questions exist about how these phenomena occur or how processes may vary under different conditions.

Creating rigorous simulations of these multiphase systems is often the best way to try to understand them. Almost all work on understanding fluid dynamics starts with the Navier-Stokes equations, which link the local movement, pressure and temperature of a fluid. An important parameter in a flow system is the 'Reynolds number', which is calculated from the domain length scale, density, velocity and viscosity of a fluid. Low values of the Reynolds number are associated with smooth 'laminar' flow, while high numbers imply turbulent flow with vortices of different shapes and length scales. This multiphase turbulent flow is, not surprisingly, harder to simulate. However, it is also much more commonly found in real-world fluid flow. The chaotic, seemingly random behaviour of turbulence cannot be solved analytically with the Navier-Stokes equations, and so must be modelled or solved using other approaches. Numerical simulations are the commonly used approaches that split the fluid up into small parcels or cells, and calculate the movement, pressure and other factors within each cell as a result of the influence of the surrounding cells. A particularly powerful numerical approach is known as the direct numerical simulation (DNS), where the Navier-Stokes equations are integrated directly without modelling. DNS can be viewed as a numerical experiment of a turbulent flow system.

DNS requires a lot of computing power and also great expertise, in order to mathematically represent the real physical processes taking place in the best possible way. Dr Lian-Ping Wang of the University of Delaware is an expert in this field, and his team has been tackling the challenges of turbulent multiphase flow using DNS. 'My work is fundamental in nature, but with a very broad application for industrial and environmental processes,' says Dr Wang.

Simulating Real-World Processes

Weather prediction relies on simulation models that predict the movement and behaviour of parcels of air at a global scale. Because of the enormous computational requirements, these parcels of air need to be quite large to avoid having too many of them for the simulation to cope with. As a result, it is difficult for global models to simulate weather conditions at a small scale (e.g. less than a kilometre). Having this information would be very important, particularly for forecasting extreme weather effects caused by climate change. This could help us to better prepare for landslides, flooding or damage to buildings and crops at specific locations.

One process of particular interest to Dr Wang and his team is the formation of raindrops from cloud droplets. This is influenced by many factors, including air humidity, temperature and pressure, but it is also strongly affected

‘My work is fundamental in nature, but with a very broad application for industrial and environmental processes, such as weather and climate, combustion, particle technology, and contaminant transport in soil’

by small-scale air turbulence. The turbulent air motion in clouds influences how the raindrops interact, grow in size and distribute in space and how the rainfall occurs. Next time it is windy and raining, look out of the window (or for the full experience, go outside). You might notice that there is a structure to the rainfall, rather than just a steady stream of water coming down. The rain comes down in sheets and bursts, which have a pattern almost like ocean waves. Simulating water particle settling velocities and growth rates in turbulent air conditions is important for understanding these localised features in rainfall.

The way in which air turbulence affects the distribution of droplet sizes and the rate of conversion of these droplets to raindrops is therefore an important topic. Dr Wang and his colleagues have shown that the influence of turbulence can be large, and that it depends on characteristics such as the rate of dissipation of turbulence kinetic energy (how quickly the turbulence transfers energy across scales and converts kinetic energy into heat).

However, simulations of rainfall formation cannot cope with the enormous range in scales involved (sub-millimetre to multi-kilometre). Dr Wang and his team have worked on incorporating the effects of air turbulence on water droplet growth and precipitation rate across many scales, and on the impact of such effects on the dynamics and lifetime of clouds themselves. They found that there are strong variations in the interactions between water droplets and turbulence, with these interactions changing greatly between small and large droplets and between different microphysical processes such as diffusional growth versus growth by collision-coalescence.

Particles in Turbulent Fluid Flow

Normally, the settling rate of small particles in a fluid (such as raindrops in air) is the same as the terminal velocity of those particles, where the forces of gravity and air resistance balance out. However, if the particles are heavy (meaning the particle-to-fluid density ratio is large) and the fluid is turbulent, this may not be the case. Studies since the 1980s have looked at this problem and have shown that particle settling rates tend to be faster than their terminal velocity, with particles accumulating along open pathways within the turbulence. Using rainfall as an example, this could result in ‘sheets’ of rain descending faster than their terminal velocity.

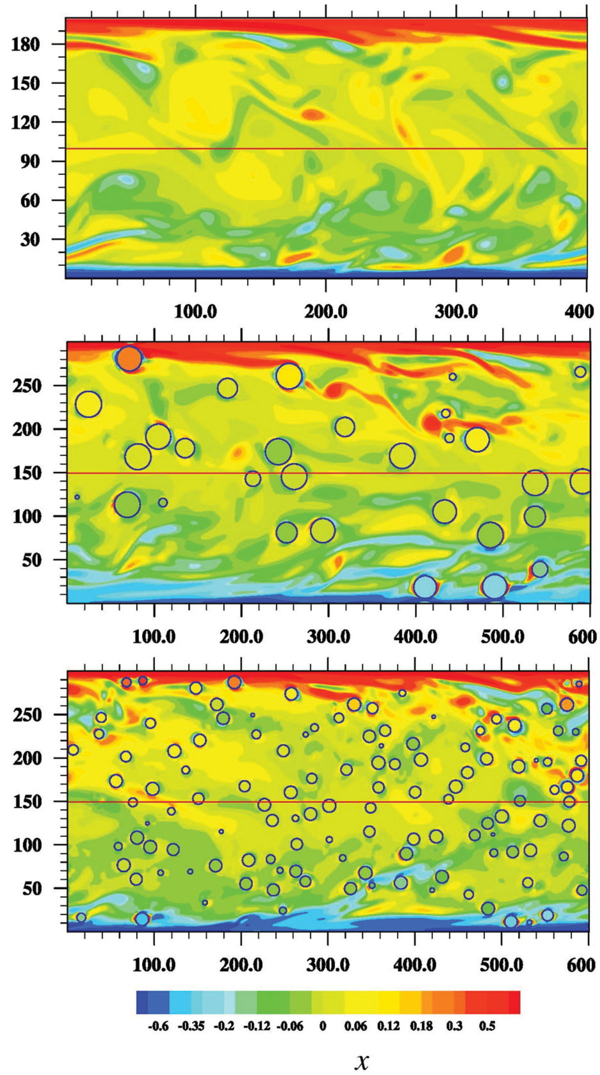
In 1993, Dr Wang and colleagues simulated this situation and showed that this effect can be much higher than previously thought. The greatest difference occurs when the particle response time is similar to the time scale of the smallest vortices in the turbulent flow. However, the organisation of large-scale turbulent vortices can also greatly influence the spatial transport and mixing of particles. An important factor in this is the ‘Kolmogorov scaling of turbulence’, which links the time scale of the smallest vortices to the viscosity (‘stickiness’) and the energy dissipation rate.

Another important factor is that the accumulation of particles in downward-moving channels in the turbulent fluid can have a feedback effect on the structure of the turbulence. If enough particles (such as raindrops) accumulate in one of these narrow channels, then they can dampen certain scales of turbulent motion and reinforce others, altering the spatial and temporal structures of turbulence. Dr Wang’s work has started to demonstrate this feedback effect and others in the interactions between the fluid flow and the particles moving through it.

Many factors such as turbulent motion, particle-particle interaction and particle-wall interaction, control the movement and distribution of particles. Dr Wang has recently been working on simulations of turbulent fluid flow containing particles of different sizes. His team aims to test out a new simulation approach and to explore what happens when different particle sizes are used. In these cases, the particle-fluid interactions cannot be represented in any other way except DNS. For the rainfall example, such particle size-resolved DNS will predict how droplet-droplet hydrodynamic interactions influence the droplet-droplet collision efficiency – a very difficult topic which is currently not well understood. This direction will provide further information about how localised rainfall patterns occur under different atmospheric conditions. This information would allow predictions of small-scale rainfall patterns, which are very difficult to simulate using current models.

Colliding and Growing

Dr Wang’s team also showed that the collision rate of particles, leading to the production of larger particles, is dependent on the nature of the turbulence within a fluid. Using a technique known as Point-Particle based Direct Numerical Simulation (PPDNS), the team was able to simulate this process. In recent years, Dr Wang developed a new method called Hybrid Direct Numerical Simulation (HDNS), which includes the local interactions between colliding particles and their effects on the surrounding turbulent



Instantaneous spanwise vorticity on a 2D slide from 3D particle-resolved simulations in a turbulent channel.

conditions. This enables the team to approximate the collision efficiency – how often the particles moving towards one another actually collide, rather than slipping past one another.

The team's work in this area has opened up new ways to rigorously address the multiscale problem of particle-fluid and particle-particle interactions in a turbulent environment, allowing different physical questions to be addressed and different conditions to be explored. Their new methods allow the mixture of particles and fluid to be simulated much more accurately than before. They have also shown evidence for simulating effects within the two-phase system that have been impossible to simulate previously. This is important, as one of the best ways of knowing that your simulation is good is if it predicts system properties that have been observed, but are not well understood. In some cases, simulations can reveal completely new phenomena that have never been observed, as observing detailed flow structures in a particle-fluid system can often be very challenging due to optical obstruction by particles.

'Warm rain formation' is where rain droplets form in clouds with a temperature above freezing. This is the most common form of droplet formation in tropical and temperate latitudes. The effects of turbulence

on droplet growth through collisions can be crucial in this type of cloud. In fact, Dr Wang's work has shown that specific cloud types (such as cumulus clouds) tend to produce a turbulent in-cloud environment, and therefore, the rainfall droplet formation taking place in them.

Rainfall is not the only process where our understanding has benefitted from Dr Wang's work. Ocean currents can be considered to be multi-phase flows, particularly when water layers with different temperatures and densities interact. In addition, the movement of water through soil is vital for water storage in catchments, and has a strong impact on flooding and plant nutrition through the transport of material. There is no shortage of examples of how this work is important for understanding natural phenomena, such as settling of sediments in rivers, transport of dust from soil erosion or the dispersion of volcanic ash clouds.

In large-scale chemical processes, particle-laden fluid flow is common. Very often, the success of the desired chemical process depends on specific particle densities and distributions within the flow. Getting the conditions right requires simulation and modelling, which can be difficult to achieve with this two-phase system (solid particles in a fluid medium).

Recent work by Dr Wang and his team has involved developing the physical systems to allow massive numerical simulations to take place. This is needed to investigate the complex behaviours seen at small scales by particle-fluid mixtures. One of the ongoing issues is the dynamics of fluid-particle mixtures flowing through rough-walled systems, such as those in industrial devices. This work will have direct commercial applications as it will help engineers better design large-scale industrial technology.

Future Work

Recently, Dr Wang and his team have been working to develop methods that can be applied generally to a wide range of different types of multiphase fluid flow. These include the flow of compressible fluids, or systems containing complex moving boundaries between fluids and solids. If methods can be developed that allow these complex fluid dynamics systems to be simulated, then it will become possible to greatly improve our understanding of a vast range of topics, including atmospheric and ocean flow, soil-water interactions and the behaviour of fluids within complex moving systems such as combustion engines, oil rigs and even volcanoes.

Meet the researcher

Dr Lian-Ping Wang
Department of Mechanical Engineering
College of Engineering
University of Delaware
Newark, Delaware
USA

Dr Lian-Ping Wang received a Batchelor's degree in Applied Mathematics and Engineering Mechanics from Zhejiang University, Hangzhou, China in 1984, and spent another two years there working on graduate coursework before coming to the US in 1986. He received a PhD in Mechanical Engineering from Washington State University in 1990, on the topic of the dispersion of heavy particles in turbulent motion. He was then a Visiting Research Associate at Brown University from 1990 to 1992, after which he was a Research Associate at Pennsylvania State University from 1992 to 1994 and an Assistant Professor of Mechanical Engineering at the University of Delaware from 1994 to 2001. In 2001 he became an Associate Professor and in 2010 he was made a Joint Professor at the College of Engineering and the College of Earth, Ocean and Environment at the University of Delaware. In 2017, he was appointed a Chaired Visiting Professor at Southern University of Science and Technology, China. He has held numerous additional visiting researcher posts at other research establishments in the USA, South Korea, Japan and China.

CONTACT

T: (+1) 302 831-8160
E: lwang@udel.edu
W: http://www.me.udel.edu/lwang/

KEY COLLABORATORS

Professor Zhaoli Guo, Huazhong University of Science and Technology, China
Dr Wojtek Grabowski, National Center for Atmospheric Research, USA
Professor Martin Maxey, Brown University, USA
Professor Shiyi Chen, Southern University of Science and Technology, China
Professor Xiaoming Li, University of Delaware, USA
Dr Bogdan Rosa, National Research Institute, Poland
Professor Yan Jin, University of Delaware, USA
Jianchun Wang, Southern University of Science and Technology, China
Professor Zhaosheng Yu, Zhejiang University, China
Professor Jingyi Yu, University of Delaware, USA
Professor David Stock, Washington State University, USA
Dr Guodong Jin and Guowei He, Institute of Mechanics, Chinese Academy of Sciences, China

FUNDING

US National Science Foundation
US Department of Agriculture
US Department of Energy
US AFOSR
US National Center for Atmospheric Research
National Science Foundation of China