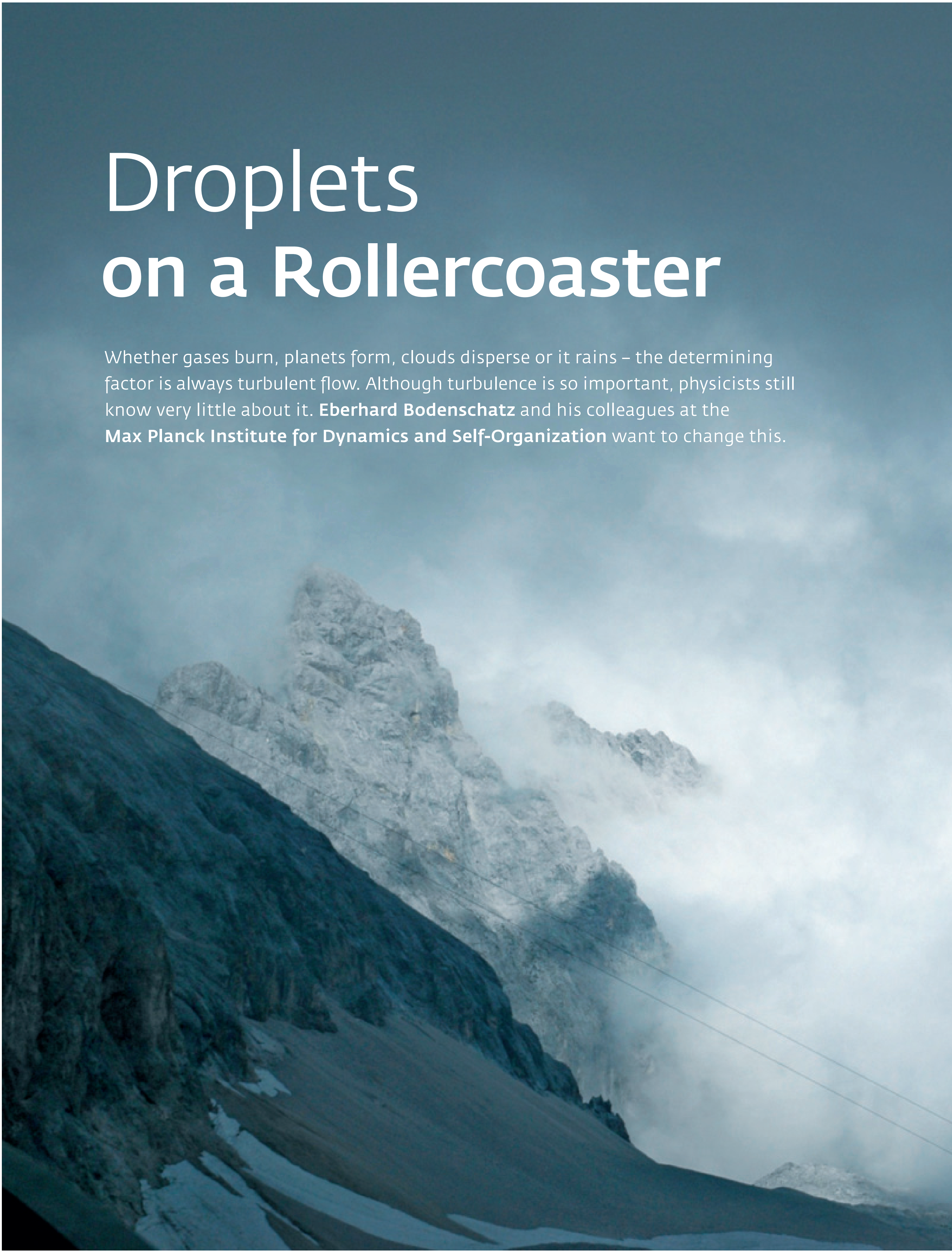
Droplets **on a Rollercoaster**

Whether gases burn, planets form, clouds disperse or it rains – the determining factor is always turbulent flow. Although turbulence is so important, physicists still know very little about it. **Eberhard Bodenschatz** and his colleagues at the **Max Planck Institute for Dynamics and Self-Organization** want to change this.



Photos: MPI for Dynamics and Self-Organization – Haitao Xu

TEXT **PETER HERGERSBERG**

When Eberhard Bodenschatz presents his research, he begins with beauty, showing images of clouds on his notebook: some big and bulky, some rather wispy, but always fluffy – and with a never ending variety of shapes. “This beauty owes to turbulence,” says the Director at the Max Planck Institute for Dynamics and Self-Organization. And in the blink of an eye, turbulence turns the white elephant in the sky into a mouse, and the prince into a frog. Without turbulence there would be only fog, as gray and boring as a dull winter’s day.

So much for the aesthetes. But Bodenschatz also provides numerous practical reasons why it is worth investigating turbulence: Turbulent flows mix the combustion gases in an engine, generate the friction of a ship cutting though the waves, control the formation of stars and planets – and determine the processes in the atmosphere. Since strong wind blows with high velocity, turbulence is generated that moves the air unpredictably with very different speeds and high accelerations. Not only are aircraft shaken about, but wind turbines do not produce electricity as efficiently as they could in a constant flow. And without turbulence, meteorologists might just also have a better understanding of how clouds form and disperse.

But the fact that a turbulent flow is particularly good at mixing particles also helps in some everyday situations. You make use of this when you stir milk into your coffee, during which you can observe the turbulence principle quite well: The stirring swirls the liquid about and supplies it with energy. The large eddy created by the stirring spoon immediately breaks up into ever smaller eddies, until finally the smallest eddies are consumed by friction. In the end, the milk has mixed with the coffee and all energy of motion has transformed into heat.

It is difficult enough in itself for physicists to describe in detail exactly what happens when milk is stirred into coffee. The whole thing becomes much more complicated when small, heavy particles, such as cloud droplets, are swirled by turbulence. Physicists can currently only begin to describe which paths the droplets take.

It is also difficult to investigate the processes in clouds because the strongest turbulence on Earth is in the atmosphere. The stronger the turbulence, the more marked is the difference between the largest and the smallest processes that occur: the largest eddies that are

Helter-skelter in the sky: In the clouds around the Zugspitze, Germany’s highest mountain, the Göttingen-based researchers investigate how droplets of mist are turbulently swirled, and how they accumulate to form raindrops.

involved in the formation of cloud droplets extend for distances of up to 100 meters, while the smallest measure scarcely a millimeter. A unit of measure for the range of the dimensions involved is given by the Reynolds number: the larger it becomes, the broader the range of values – and the stronger the turbulence.

A WIND TUNNEL FOR STRONG TURBULENCE

If atmospheric scientists want to forecast the fate of a cloud, they must know how turbulent the rollercoaster ride of the particles is – in this case the droplets in a cloud. The motions of the particles also decide how often they collide, meaning how quickly the cloud droplets are transformed into raindrops. This is how the cloud finally falls from the sky. Moreover, turbulence mixes dry and wet air, and cold and warm air. "As long as we are unable to realistically describe these processes, the climate models lack the equations needed to make a better forecast of the cloud cover and thus climate development," says Eberhard Bodenschatz. He and his colleagues are thus working on acquiring a better understanding of turbulence. And since this is a giant undertaking, they need a giant device to complete it.

The laboratory that the researchers have built for this task is easily as big as a school gym. The high-pressure turbulence system extends down the length of the hall – a bright red pipe, taller than a man, which bends to form an elongated closed loop. One of the two 18-meter long main pipes rests in bulky supports just above the floor; the other is about 3 meters higher. Through the loop of the tunnel, the researchers will blow a wind that, at one section, must pass a grille with flaps arranged like a chessboard. "By deliberately closing individual flaps, we generate different turbulent flows," explains Holger Nobach, the electrical engineer in charge of the construction of the wind tunnel. And at forces that can otherwise be observed only in the atmosphere.


1


2

1 In the wind tunnel, Eberhard Bodenschatz inspects the measuring device that measures the speed of the flow.

2 For the next round in flow research: The high-pressure wind tunnel in Göttingen makes it possible to investigate the paths of individual particles in extremely strong turbulence.

3 The team behind the camera: Haitao Xu, Eberhard Bodenschatz, Gregory Bewley, Ewe-Wei Saw, Holger Nobach and Hengdong Xi (from left to right). In the foreground, the track upon which a measurement carriage with cameras will follow individual particles in the turbulence.


3

In order for the flows to be swirled as turbulently as in the atmosphere, the researchers send not only air through the wind tunnel, but sulfur hexafluoride as well. Its molecules have a particularly high mass and naturally provide the gas with a high gas density. Moreover, the Göttingen-based physicists can compress it up to 15 times atmospheric pressure. Dense gases make it possible to create the turbulence as it occurs in all weather conditions. They can do this without having to use similarly drastic power to generate the whirling motion, as dense gases have a low effective viscosity – what physicists refer to as kinematic viscosity.

Viscosity indicates how well a gas or a liquid flows. High viscosity thus corresponds to a slow-moving affair. For example, honey has a higher viscosity than air. The kinematic viscosity is needed if accelerations play a role, as is the case with turbulence. The density of the gas or the mass of its molecules then influences the flow behavior. The denser the gas, the more inertia it has, and the larger the force needed to slow it down. This is ultimately how dense gases make it possible to create strong turbulence in a device that is dwarfed by the size of a cloud.

The researchers will chase tiny particles through the wind tunnel with the compressed gas, and film them live as they ride the turbulent flow. This they accomplish by driving three cameras mounted on a carriage along a track. The system is separated from the turbulence by a plate of Plexiglas and stretches over the floor of the upper main pipe. Each of the three cameras will take up to 30,000 images per second of the test particles, thus tracking their path. Eberhard Bodenschatz worked out this measuring principle when he was still at Cornell University in Ithaca, New York – and opened up a completely new perspective on the phenomenon by making it possible to view individual particles on the rollercoaster of the turbulence.

LIVE RECORDING OF THE SWIRLING PARTICLES

This approach is named after scientist Joseph-Louis Lagrange, who developed the mathematical tools to turn the results of the measurements of individual particles into a theory. But it is a completely different measuring principle than the one that revealed what physicists currently know about turbulence in clouds. It involves the researchers virtually sitting at one location and measuring the fluctuating speeds with which air or another medium flows past them. This view of turbulence is called Eulerian, again named after the researcher who laid down the mathematical framework. The speed fluctuations are then measured by a red-hot wire through which an electric current flows. Its resistance reacts with extreme sensitivity to the cooling effect of the gas flowing past, and the cooling effect is all the more evident the faster the gas flows.

"Such measurements have enabled many fundamental observations to date, and go back about a hundred years," says Haitao Xu, who also conducts research into turbulent flows in Eberhard Bodenschatz's department. Eulerian measurements have provided a good picture of the velocity field that prevails in turbulent flows. However, these experiments have provided no insight into the accelerations that particles experience in the process, because in order to be able to make statements on this, it is not sufficient to measure how fast particles move at a given time and location. The physicists can determine the acceleration of the particles only if they track their flight. And the measurements devised by Eberhard Bodenschatz and his team enable them to do exactly this.

In fact, in the first studies carried out in accordance with the Lagrange principle, the physicists immediately discovered that the particles in a turbu-

Photos: Norbert Michalke (3)

Just the spot for cloud droplets: Eberhard Bodenschatz and Haitao Xu set up an instrument that follows the paths of individual droplets with a laser.

lent flow are accelerated much more abruptly than expected. The acceleration of a cloud droplet therefore fluctuates considerably. In a cloud, on average, the acceleration by turbulence is as high as the gravity and can peak at more than 20 times this. "This result shows that the collisions of droplets in clouds, and thus their growth, cannot be forecast with any degree of reliability if we take only the average acceleration into consideration," explains Eberhard Bodenschatz. How often collisions occur thus depends not only on how the majority of the particles behave; it is determined primarily by the small group of particles that, although rare, are particularly strongly accelerated. They very frequently end up on a collision course.

STRONG ACCELERATIONS LEAD TO MORE COLLISIONS

So the strong fluctuations in the acceleration could also explain why droplets in clouds come together more quickly than the conventional theory allows. In order to test this, the researchers in Göttingen want to conduct the experiment under the extremely rough conditions that prevail in clouds. The first measurements for this will start as early as this year in the high-pressure wind tunnel.

In further experiments, the researchers also want to find out whether cloud droplets are able to follow turbulent air flows at all – a daunting task. Compared with the air molecules, even the tiny cloud droplets are gigantic lumps. They are thus easily hurled out of the strongest eddies of the turbulence, just as a truck that moves with the flow on a highway filled with nothing but cars also leaves the lane more easily in a curve.

If the truck is fast – like a cloud droplet that gets caught in the center of a violent eddy – it is pushed into the lanes with opposing traffic. That is why trucks tend to chug along rather leisurely through curves. However, the same applies to a cloud droplet as applies to trucks: The violent eddies with their narrow curves and rapid changes in velocity catapult the cloud droplets out of the area with speedsters and they end up on a collision course. The droplets should thus collide more often and form raindrops in very turbulent clouds than in calmer air. "So far, we have not been able to observe this in clouds and, interestingly, it is the very rare occasions of rapid change in velocity," says Eberhard Bodenschatz. "It's like with earthquakes: it's not the rumbling of the ground, but the very rare major events that matter."

On another question, which only those who have exact knowledge of turbulent flows can answer correctly, the physicists have already made some progress by observing individual particles – namely the question of how fast two fluids mix in a turbulent flow. The answer to this could contribute to solving many geoscientific and technical problems.

Photo: Leibniz Institute for Tropospheric Research – Holger Siebert

Physicists use the term fluid to describe any substance that is able to flow, and usually mean liquids or gases, but also smoke or solid particles suspended in a fluid. Examples for the mixing of two fluids are moist air in clouds that mixes with the dry air around it, as well as the billows of smoke from a chimney that disperse in the clear atmosphere. How fast this mixing occurs can be estimated by how fast, for example, the paths of two particles separate as they rush through the turbulence. That turbulence is particularly effective at mixing the substances is clear, but how this happens in detail is not.

UP IN THE CLOUDS – RESEARCH ATOP THE ZUGSPITZE

That is why Eberhard Bodenschatz and Haitao Xu also followed the process in a model system with a camera. Accordingly, two or more particles may separate as quickly as the long-accepted theory predicts only if the flow is very turbulent. The physicists usually also have to take the initial distance between the particles into account in order to calculate how fast they drift apart.

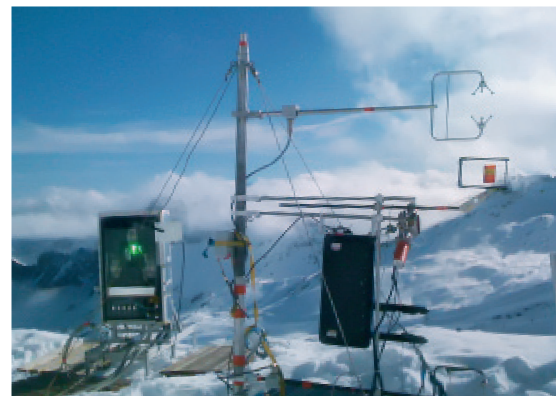
The following then applies: The closer the particles were at the beginning, the faster they go their separate ways. This may sound surprising, but there is a simple explanation: The large eddies of the turbulence remain stable longer than the small ones. On the large scale, the particles are guided together in a circle for a long time, but their paths diverge quickly on the small scale when their small shared eddy dissolves.

"To test whether our assumption also holds for the separation of tiny droplets, we still need to conduct our experiments at higher Reynolds numbers," says Haitao Xu. The experiments in the laboratory assist the researchers in clarifying the laws that very strong turbulence obeys. For this they need conditions that can be very precisely controlled, like in the wind tunnel.

However, these experiments still do not provide the certainty that the droplets in natural clouds behave exactly as the particles in the wind tunnel. They will therefore also use their technique to observe the droplets in real clouds – at the place in Germany where one is probably closest to the clouds: atop the Zugspitze, or more precisely, in the Schneefernerhaus environmental research station.

This is where, in summer, the researchers from Göttingen will install a measurement carriage for the camera in order to look into the clouds. "In order to be able to take 10,000 images per second of the droplets, we need a very strong laser," says Haitao Xu. He and his colleagues tested the system last year: "And it worked well."

Eulerian measurements are planned to complete the picture. They have also installed these instruments on the Zugspitze. And colleagues at the Leibniz Institute for Tropospheric Research and Michigan Technical University (USA) are using the most modern instruments available for meteorological investigations on the Zugspitze, and have also packed them into the Actos measuring unit. This is suspended from a rope and dragged through clouds by a helicopter. The researchers ultimately want to use these instruments to make a contribution to more reliable climate forecasts. But not only that: they also want to refute a skeptical statement by British physicist Horace Lamb, who said in the 1930s: "… when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic." ◂



Clouds under around-the-clock observation: Atop the Zugspitze, partners of the researchers in Göttingen measure such things as particle size and speed, as well as water content and temperature.

GLOSSARY

Reynolds number
Put simply, this is a measure of the intensity of turbulence. It gives the range covered by the values of characteristic parameters, so for example the different dimensions of the eddies. The higher the Reynolds number, the greater the difference between the largest and the smallest eddies.

Kinematic viscosity
Indicates the effective viscous force in a liquid or gas. The viscous force is caused by the friction between particles, the inertial force by the mass or density of the fluid. Kinematic viscosity decreases when density increases. It defines the flow behavior of the fluid when it is accelerated.

Lagrangian measurements
Follow the flight paths of individual particles. They thus permit statements on the speed and acceleration of a particle.

Eulerian measurements
Determine the speed of turbulent flows at one or several points simultaneously. These measurements can be used to obtain the velocity profile of the turbulence.

Photos: MPI for Dynamics and Self-Organization