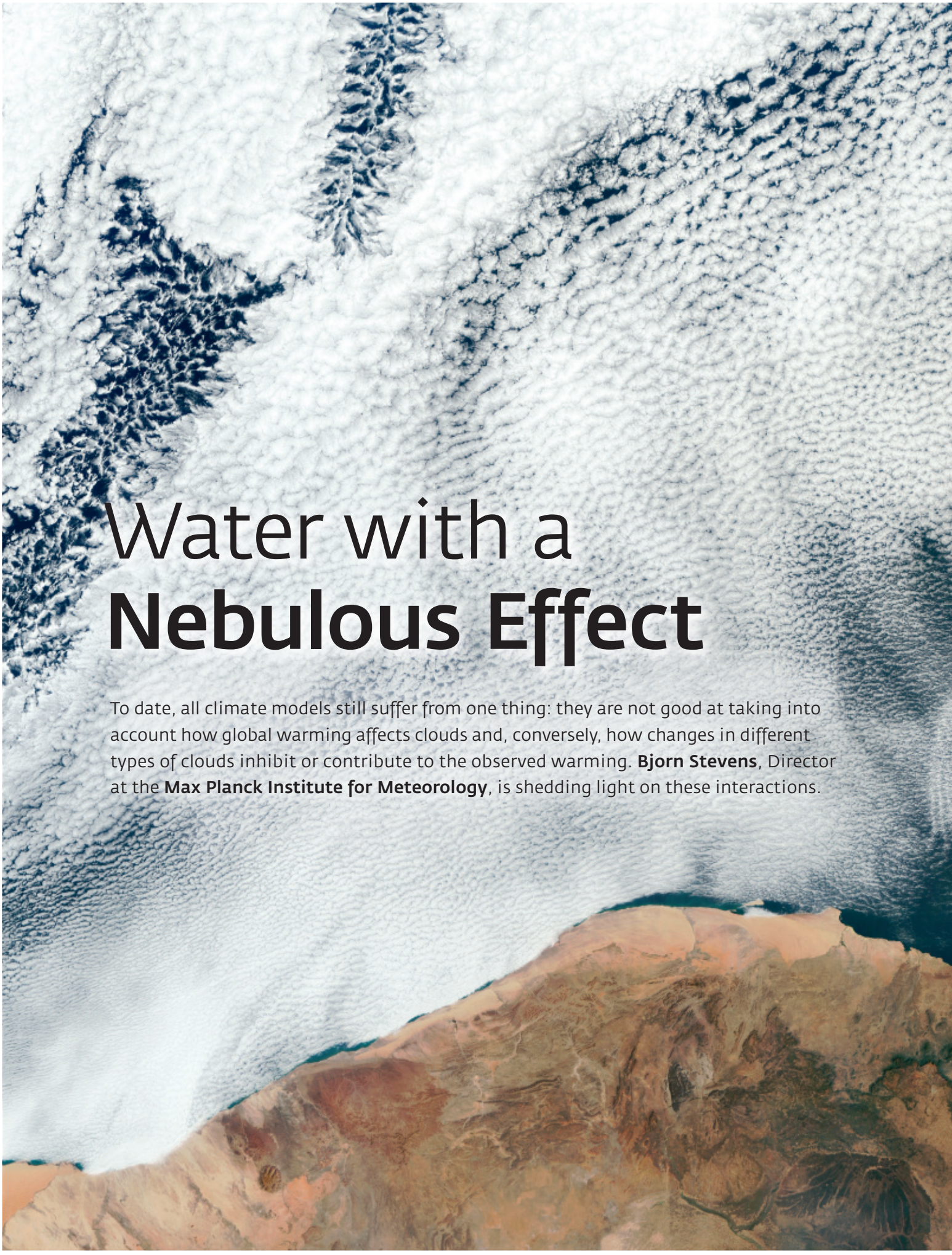


Water with a **Nebulous Effect**

To date, all climate models still suffer from one thing: they are not good at taking into account how global warming affects clouds and, conversely, how changes in different types of clouds inhibit or contribute to the observed warming. **Bjorn Stevens**, Director at the **Max Planck Institute for Meteorology**, is shedding light on these interactions.

Photo: Jacques Descloitres, MODIS Land Rapid Response Team, NASA/GSFC

TEXT **CHRISTIAN MEIER**

According to René Descartes, they formed God's throne: clouds. The French philosopher also considered the flowing and temperamental shapes of the fluffy weather phenomena to be the ultimate litmus test for human cognitive powers. Those who understand clouds, wrote the originator of rationalist thinking in the 17th century, would have the means to explain all things wonderful on Earth.

Descartes' words on the significance of understanding clouds thus remain topical, at least as far as climate research is concerned. For the science that deals with the Earth's atmosphere, it really does turn out to be a litmus test. The floating mists play a dual role in the Earth's climate: they cool the surface by reflecting sunlight into space and, at the same time, they warm it by preventing infrared radiation from escaping from the Earth's surface into space. This two-faced quality makes it more difficult to forecast whether changes to the cloud cover caused by the climate slow down global warming, accelerate it, or do neither. The only thing that is clear so far is that even a small change in the cloud cover can make the forecasts of the climate models obsolete.

"If the cloud cover were to change by a mere five percent or so as a result of climate change, this could cancel out the effect of a doubling of the

Cooling cloud cover: Marine stratocumuli like these off the coast of southwest Africa reflect the sunlight. Will their number increase as the climate changes?

greenhouse gas carbon dioxide, or it could double it," says Bjorn Stevens, Director at the Max Planck Institute for Meteorology in Hamburg, illustrating the role that clouds play in determining the Earth's climate. A scarcely noticeable increase or decrease in clouds may affect the climate at least as much as a further doubling of the carbon dioxide content in the atmosphere. It is no wonder, then, that clouds are the most uncertain factor in climate researchers' models.

CLOUD ALTITUDE DETERMINES THEIR CLIMATE EFFECT

Stevens wants to remove the uncertainties. He is one of the researchers who want to realize Descartes' dream of understanding clouds. But how can researchers hope to grasp something that exhibits so many forms and seems to change so erratically as clouds? At the beginning of the 19th century, British amateur meteorologist Luke Howard was the first to recognize that clouds do not behave as chaotically and arbitrarily as it seems. He devised a scheme, which is largely still in use today, that divided the various clouds into a small number of categories. He called his basic cloud types cirrus, cumulus and stratus.

Every cloud in the sky can be characterized as one, or a combination, of these types. Cumulus, for example, means heap in Latin and describes compact clouds that are heaped upon each other above a broad flat base, like a heap of stones. Stratus means layer, and refers to a cloud-covered sky. Meteorologists therefore use the term stratocumuli for a blanket of cloud comprised of densely packed cumuli. The altitude of the clouds provides a further criterion for distinguishing between them. There are three stories, so to speak: low clouds, in technical jargon low-level clouds, romp about at heights up to about 2,000 meters above the surface; medium-level ones, given the prefix alto, between 2,000 and 6,000 meters; and the high-level cirrus clouds float at more than 6,000 meters above sea level.

The altitude of the clouds determines their effect on the climate: high-level clouds impede the Earth's attempt to cool itself through the emission of infrared radiation and thus warm the surface, while low clouds mainly reflect sunlight and cool the surface. This can be understood by considering the temperature of the clouds, which depends on their height, and which in turn determines how much energy they radiate. Seen from space, the cold high-level clouds radiate relatively little heat. By not allowing heat radiation to escape into space from the warmer Earth's surface, which is hidden by the high-level clouds, high clouds act to warm the atmosphere. Low-level clouds, on the other hand, emit almost as much heat radiation into space as the Earth's surface below, which isn't much warmer. This means that they greatly impact the rate at which the Earth radiatively cools. But low-level clouds are more compact than the veil-like cirrus clouds at that altitude, and they reflect more sunlight into space than would the underlying surface.

What's gathering over there? Bjorn Stevens on a balcony of the 'Geomatikum' at the University of Hamburg. A laser instrument that measures the intensity of the precipitation is seen on the right.

"In order to be able to calculate the role clouds play in climate change, we need to know how the occurrence of the high-level and low-level cloud types changes," says Stevens. The fundamental question is: How do the different types of clouds react to changing conditions in their environment, such as changes in temperature or humidity? If high-level and low-level

Photo: David Ausserhofer

» The fundamental question is: How do the different types of clouds react to changing conditions in their environment, such as changes in temperature or humidity?

clouds increase equally, the two effects could offset each other, resulting in little net heating or cooling of the surface. If, however, the high-level clouds were to increase and low-level clouds decrease, the temperature of the Earth's atmosphere would increase more strongly than would be caused by the carbon dioxide increase alone.

Clouds also consist of components of different sizes. The smallest floating cloud droplets just manage to reach a diameter of one hundredth of a millimeter, a falling raindrop measures more than one millimeter, and the air eddies of the turbulences in clouds exhibit diameters ranging from one millimeter to around one hundred meters.

Cumulus clouds in various shapes cover large parts of the oceans. They are of particular interest to Stevens.

Photo: Stephan Borrmann

Stevens and his colleagues must understand the appearance and disappearance of the various cloud types in order to be able to calculate how they react to changing conditions. This task is probably little easier than understanding the birth and death of a living being, as the circulation of moisture on Earth, which is manifest in the clouds, proves to be as complex as an organism whose function depends just as much on the tiniest cell as it does on its organs and, ultimately, its entire body.

A complete cloud can extend for kilometers; cloud fields can even stretch across hundreds of kilometers. Finally, large-scale moisture cycles cover distances of several thousand kilometers.

"On each of these dimensional scales are many physical processes that are still poorly understood," says Stevens. The crux of the problem is that the processes influence each other across dimensional boundaries. "You cannot simply take out a part, explain it and put it back again," says Stevens, explaining the difficulties of the undertaking. The trick is to investigate part and whole together by jumping back and forth between them.

CLOUDS CHANGE LOCALLY BUT HAVE GLOBAL IMPACT

The scientist illustrates the link between "very small" and "very large" with turbulent air currents, which are assumed to be decisive for the lifespan of clouds. Aircraft passengers often feel them when the plane shakes. At the edges of a cloud, the turbulence mixes the dry, clear surrounding air with moist cloud air. Atmospheric scientists call this mixing entrainment. The dry air mixed into the cloud affects the water droplets in the cloud. It can change the distribution of their size so that more extremely small or extremely large droplets are formed, which in turn affects the tendency of a cloud to give rise to rain. However, the entrained dry air can also cause the water droplets to evaporate and thus dissipate the cloud.

Entrainment occurs on a practically microscopic scale when compared with the size of clouds: the air eddies involved have diameters of between a few millimeters and a few meters. The effect of entrainment can also be global. If clouds over the frequently cloud-covered southeast Pacific Ocean disperse, for example, the Sun's irradiation on this part of the ocean increases and it becomes warmer – a development that has the potential to contribute to seemingly unrelated phenomena, such as El Niño. "Before we can forecast such climate phenomena as El Niño with certainty, we have to understand many details of cloud physics, including how strongly the entrainment in the southeast Pacific Ocean contributes to the dispersion and evaporation of clouds," says Stevens.

The task of cloud researchers is made even more difficult by the fact that processes like entrainment are not

Rain on the board:
Bjorn Stevens explains which factors influence the structure of tropical rain clouds.

of equal importance for all cloud types. Each cloud type must therefore be investigated individually.

CUMULI COVER LARGE PARTS OF THE OCEANS

Stevens is focusing his efforts on certain types of low-level clouds over the tropical and subtropical oceans. These are widespread and therefore particularly important for the climate. Moreover, Stevens thinks they are relatively easy to understand, as they contain no ice. Ice complicates the cloud problem enormously: depending on the temperature and air humidity, ice crystals assume very different structures, ranging from snowflakes, ice needles and platelets to sleet and hailstones. And different ice forms have a different effect on the formation of precipitation.

Stevens has been studying one type of low-level cloud for many years: marine stratocumulus clouds, which cover more than one tenth of the ocean expanse and are thus relevant for the climate. This type of cloud forms over cold sea regions of the subtropics, such as off the Californian and South American Pacific coast and the Atlantic coastline near Namibia. In these regions, there is a layer of cool moist air around 900 meters thick under warm dry air. Directly below the boundary between cold and warm air, a closed blanket of densely packed convective clouds often forms – the stratocumuli.

Stevens has investigated the entrainment of these clouds. For decades, meteorologists wondered whether specific processes could spontaneously break up the marine stratocumuli. They assumed that the entrainment self-amplifies under certain circumstances, like a chemical reaction that produces its own catalyst. This would mean that the dry zone, driven by the entrainment, grows relatively quickly into the cloud from above and thus evaporates it.

Before Stevens' research, estimates of the efficacy of such a process were very uncertain, with estimated rates of drying varying by an order of magnitude. Stevens therefore decided to recheck the measurements. Eight years ago, when he was still a professor at the University of California in Los Angeles, he used an old military transport plane, equipped with instruments for measuring quantities of meteorological interest, to fly into the stratocumulus clouds off the California coast. The measurements formed the basis for a computer model of the turbulence at the edge of the cloud. This model narrowed the uncertainty by more than a factor of five, and ultimately revealed that the mixing progresses "too slowly for the entrainment to be able to disperse the stratocumuli spontaneously," explains Stevens.

Even if the entrainment does not suddenly wipe stratocumuli from the sky, satellite images nevertheless show curious "holes" in otherwise solid decks of clouds. The phenomenon is astonishing: seen from above, the clouds form a grainy surface, reminiscent of a multicellular organism. The white cells – the clouds, which can measure 5 to 50 kilometers in one direction – are framed by dark edges where the clouds are thin or absent and the ocean lying below is apparent. At some places, in the center of the blanket of cloud, the pattern is reversed: the cells appear dark with white edges. This is where the clouds in the inside of the cells have disappeared; instead, some have formed at the edges of the cell that had previously been cloud-free – as if one were looking at the negative of a photograph of the original pattern. Measurements from Stevens' airborne mission showed that the stratocumuli, which normally do not tend to cause heavy rain, rained at the transition to this negative pattern.

Photo: David Ausserhofer

» Clouds always form when warm, humid air rises. The process explains how fusing water droplets can ultimately reverse kilometer-long air currents.

Stevens explains why they do this as follows: The generally thin stratocumulus cloud layers can thicken due to a local accumulation of moisture, and thicker clouds produce larger drops and thus rain easily. Larger drops fall more effectively through a background of small cloud droplets, as they experience less air resistance relative to their mass.

RAIN REVERSES UPWARD AND DOWNWARD FLOWS

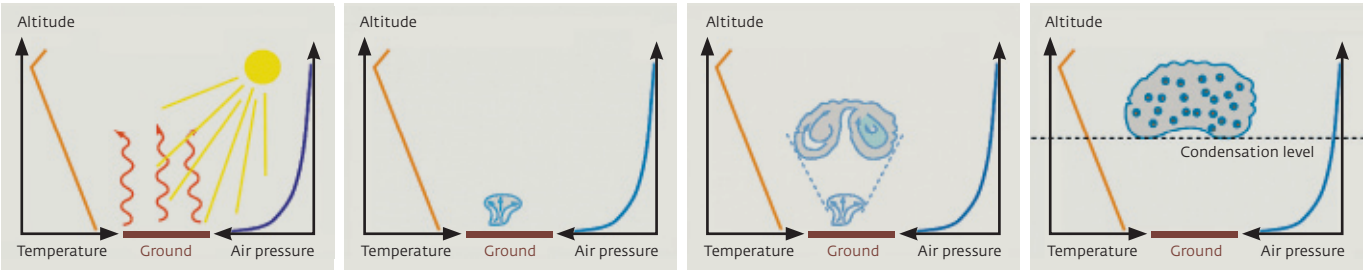
These larger cloud drops fall through the cloud, catching up and colliding with smaller droplets below. They coalesce with some of these droplets, become larger and fall even faster. A type of snowball effect occurs, and the droplet grows to a million times its original mass. Sufficiently large drops fall so quickly that they reach the surface of the ocean as raindrops without evaporating again. This is particularly easy in thicker clouds, as they offer the droplets a relatively great height of fall, which gives the proto-raindrops more time to collect cloud droplets on their way down.

The rain from the low-reaching clouds is not without consequences: computer simulations that Stevens undertook with his former doctoral student Verica Savic-Jovcic showed that, when it rains, the circulation of the moist air between the ocean and the cloud layer can change radically. Non-raining clouds are dominated by a strong upward flow in the center of the cell, with weak downward flows at its edges. Afterwards, it reverses: there is a strong downward flow in the center and weak upward flows at the edges. This reversal of the flows causes the original pattern of the cloud blanket to turn into its negative, because clouds form more readily when warm, humid air rises. The process explains how fusing water droplets that cannot be seen with the naked eye can ultimately reverse kilometer-long air currents.

Now that Stevens and his colleagues have gained a better understanding of the stratocumuli, they are taking the next step. "We are currently incorporating the results into the global climate models," says Stevens. These computer models divide up the atmosphere into grid boxes – pancakes, really, as their length and width measure several hundred kilometers and may be hundreds of meters to a kilometer thick. For each of these boxes, the computer calculates average values of temperature, humidity and other characteristics of the atmosphere.

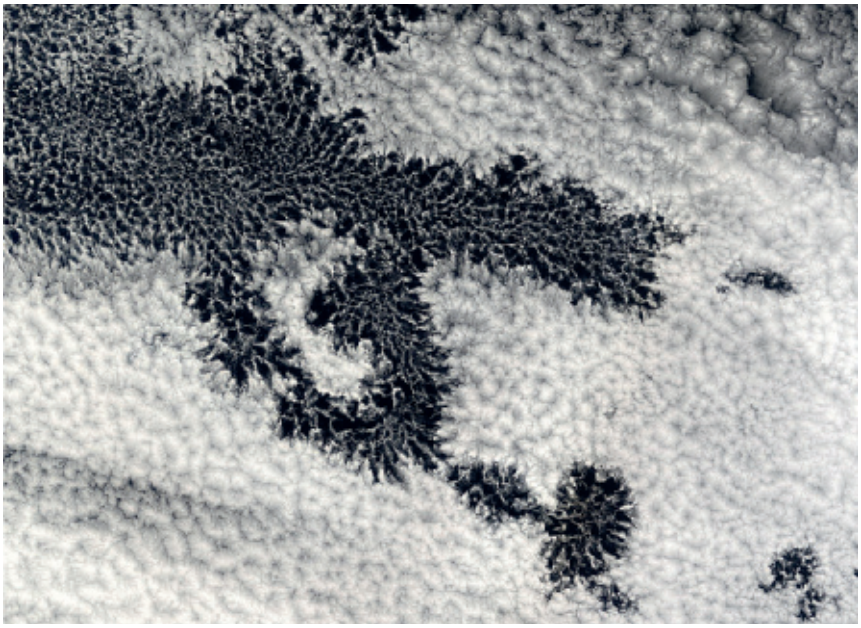
Since clouds are typically much smaller than a grid box, they slip though this grid, which is to say that the climate models fail to simulate them explicitly. The researchers cannot use smaller grids, as this would increase the computing time to immeasurable proportions. However, when researchers have understood the physical processes in the individual types of clouds, they can make do. They may still not be able to calculate the exact locations in the grid where the individual clouds will form, "But the statistics of the cloud distribution can be calculated on the basis of the average values of parameters like temperature and air humidity, which the computer model computes," says Stevens. It is then also possible to say what percentage of the grid volume is filled with

FORMATION OF CLOUDS BY CONVECTION (RISING AIR)



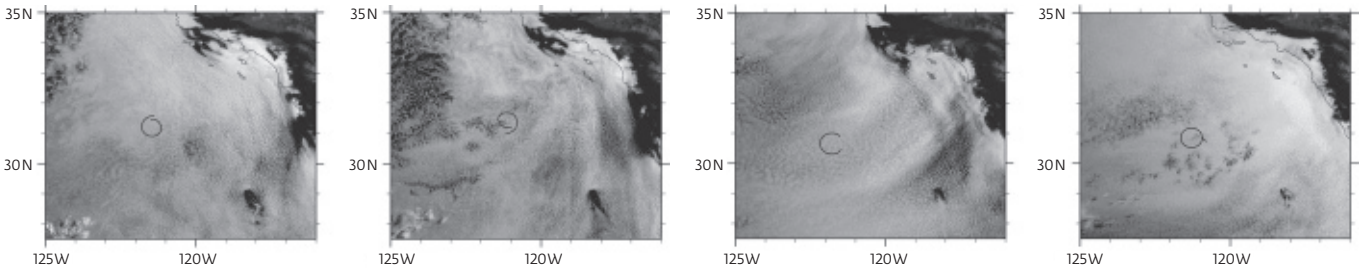
A cloud in the making: Sunlight heats the ground so that the air above it heats up and warm air bubbles rise. With increasing altitude, the bubble expands and cools until the air humidity condenses. Turbulent flows, as in the second image from the right, mix the moist cloud air with the surroundings so that low-level cumulus clouds sometimes disperse again. The temperature and pressure decrease with altitude, as can be seen at the left and right edges.

Graphic: Stephan Borrmann



right: Marine stratocumulus clouds first form a pattern of white cells at whose thinned edges the dark underlying sea becomes apparent. When they precipitate rain, the pattern reverses.

below: Measurement paths: The dark lines represent the paths that an aircraft flew through the stratocumulus field in order to collect physical data.



clouds and with which types of clouds. This then makes it possible to quantify the influence of the clouds on heat and solar radiation.

TURBULENT RAIN FORMATION

Stevens is now also devoting himself to a second type of low-level cloud over the tropical oceans, the so-called low-level cumuli. These fair-weather clouds are omnipresent over the warm oceans – they cover around 40 percent of the world's oceans – and Stevens believes that they thus exert an even greater influence on the global climate than stratocumuli.

Together with Axel Seifert from the German meteorological service Deutscher Wetterdienst and his doctoral student Louise Nuijens, he recently investigated how rain forms in such a cloud. The researchers showed that turbulence can decisively assist the rain formation in the cloud, because the air eddies help distribute water droplets in a way that makes them more likely to collide. The droplets thus fuse more often and ultimately produce more droplets that are heavy enough to fall; in doing so, they collect more small droplets and finally become drizzle, and then raindrops. Computer simulations have shown that turbulence increases the frequency of droplet collisions by a factor of more than four. "So the cumuli can form rain somewhat more easily than we had thought," says Stevens.

Stevens doesn't want to investigate the low-level cumuli only via computer. His office at the Max Planck Institute in Hamburg contains visible evidence that his research rests on two pillars: equations and sketches cover a board on the wall. Directly next to it, on a side table between a group of chairs, is a model of the *HALO* research aircraft, whose turbulence probe stretches into the sky from its nose. The German Aerospace Center manages this vessel for the German research community (see box, page 27). Stevens uses a combination of theory and fieldwork. On a mission that Stevens is organizing, *HALO* will soon fly through fair-weather cumuli off the coast of the Caribbean island of Barbados, using various instruments to measure droplet sizes and turbulence.

THERE IS NO UNIVERSAL FORMULA FOR CLOUDS

On the island itself, the Max Planck researchers are joining forces with researchers from the Caribbean Institute for Meteorology and Hydrology in Barbados, the University of Miami and the Leipzig Institute for Tropospheric Research, and are in the process of installing remote sensing instruments: radar instruments and a special laser for measuring humidity and aerosol layers. Their purpose is to target the clouds coming in from the open sea. "The data will help us explain the relationships between cloud cover, precipitation, the aerosol and the properties of the air surrounding the clouds," says Stevens.

The cloud researcher is not only very optimistic about this measurement campaign, but also about the future of cloud research as a whole. "We

Photos: MPI for Meteorology (top), center illustration from: M.C. van Zanten et al.: Journal of the Atmospheric Sciences, Volume 62, Issue 12 (2005), pp. 4327-4342 (bottom, 4)

Some stratocumuli, such as those here near the Galapagos Islands, easily form drizzle and evaporate. This causes the upward and downward air flows to reverse.

Photo: Stephan Borrmann

will learn far more about clouds in the next 25 years than we have learned over the last 25 years," he says, visibly pleased. The observation techniques were developed during the last quarter of a century. "Now we are using them." Satellites have since been able to produce three-dimensional images of clouds and their interior with the help of radar and laser beams. In addition, the increasing computing power of computers has been making it easier and easier to simulate physical processes simultaneously on an increasing number of dimensional scales – of course only after the relevant processes were understood.

CLOUD RESEARCH IS LIKE A JIGSAW PUZZLE

But Stevens does not believe in a kind of universal cloud formula: "I don't believe that there is such a thing as a general principle that uses a couple of mathematical symbols to explain the complete physics of clouds," says Stevens. He compares cloud research with cancer research. "Medical researchers used to believe there was a general mechanism that can explain cancer. Now we know that each type of cancer needs to be researched on its own," says the scientist. It's a similar situation with clouds: each type of cloud must be understood for itself. The fact that entrainment does not work efficiently for the marine stratocumuli, for example, does not necessarily mean that the same goes for other cloud types. Cloud research thus resembles a jigsaw puzzle: the greater the number of pieces that are filled in, the easier it is to see the whole picture.

Bjorn Stevens agrees with Descartes' statement that clouds provide the key to understanding the whole world – but with a few reservations. The processes in the Earth's atmosphere can indeed be understood only by those who penetrate the clouds. But not much more – and he adds: "If I ever succeeded in completely understanding the clouds, I would probably still find it difficult to understand some of the decisions made by politicians." ◂

GLOSSARY

Low-level cumuli
Cumuli clouds at altitudes up to 2,000 meters above sea level. These fair-weather clouds cover up to 40 percent of the oceans.

Marine stratocumuli
A blanket of low-level cumuli that occur above cold subtropical oceanic regions and cover around one tenth of the oceans.

Entrainment
The process by which turbulence at the cloud edge expands into the cloud-free region, mixing moist cloudy air and dry air from the surroundings and evaporating the cloud. This process encompasses scales between millimeters and hectometers.

El Niño
Is based on a reversal of the normal ocean circulation between Indonesia and Peru and occurs at irregular intervals around Christmas time (El Niño (Span.) = Christ child). Extremely warm water from Indonesia thus reaches Peru, causing plankton to die off and the food chain to collapse. Since the climate is coupled to the ocean circulations, El Niño influences the weather in many parts of the world.