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The CLOUD DYNAMICS of convective storm systems

Caroline Muller and
Sophie Abramian

Through a combination of idealized simulations and real-world data, researchers are uncovering how internal feedbacks and large-scale motions influence cloud dynamics.

People are delighted by clouds and have been ever since first looking up at the sky. They have fascinating structures, which help observers to visualize atmospheric motion. Convective clouds form when air rises. Convection here refers to the movement of air within which clouds are embedded, as shown in figure 1a. Air can rise as a result of the warming of Earth's surface during the day or as it moves over mountains and other topographical features.

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Caroline Muller is a professor at the CNRS in Paris and the Institute of Science and Technology Austria in Klosterneuburg. **Sophie Abramian** is a PhD student at the Pierre Simon Laplace Institute's Laboratory of Dynamic Meteorology in Paris.

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The air's upward movement carries near-surface water vapor, whose large concentration at low altitudes decreases rapidly with height in the atmosphere. Through a process known as adiabatic expansion, the rising moist air cools as the pressure drops at higher altitude. When the moist air is cold enough, its water vapor starts to form liquid or ice condensates, depending on temperature. The tiny, suspended condensates—typically a few tens of microns in diameter—form clouds, which unlike water vapor are visible to our eyes.

At the mature stage of cloud formation, the rising air reaches its equilibrium level—the altitude where its density matches that of the environment—and the cloudy air is no longer buoyant (figure 1b). For dense, deep clouds, the equilibrium level can be as high as the tropopause, an altitude of around 10–15 km.

Once the air stops rising, it spreads horizontally at the top of the cloud and forms what's called an anvil cloud, shown in figure 1c. The condensed droplets grow in the cloud through microphysical processes, and when large enough, they eventually start to precipitate and fall toward the ground. As they do so, they may partially evaporate, notably below the cloud base. The concomitant latent cooling leads to a cold air mass, known as a cold pool, that descends below the cloud and spreads horizontally at the surface. The downward motion counteracts the upward motion that started the convective storm, thereby ending the cloud life cycle. The whole process for a single cloud typically lasts a few hours and spans a horizontal scale of roughly one to a few kilometers.

Clouds can also form spectacular multicloud structures, several of which are shown in figure 2. At scales of hundreds of kilometers—the so-called mesoscale—organized convection can take the form of squall lines or mesoscale convective complexes. The most famous example is probably the tropical cyclone. At its center lies a relatively quiet eye, surrounded by a cloudy wall of rotating winds, which are among the strongest on the planet.

Mesoscale organized systems like the ones shown in figure 2 lead to extreme weather and to changes in large-scale properties, notably cloud cover and water-vapor distribution. Although the physical processes that cause mesoscale organization are still poorly understood, the science is improving because of significant advances in the past decade. The breakthroughs were made possible by the increased capability of computer simulations and by many idealized and theoretical investigations. Notably, much progress has been made on a mode of convective organization called self-aggregation.

Self-aggregation by internal feedbacks

Self-aggregation refers to the spectacular ability of deep clouds to spontaneously cluster in space, despite perfectly homogeneous boundary conditions in idealized numerical simulations[1] (see figure 3). The phenomenon occurs when sea-surface temperature is constant, with neither large-scale forcing nor land–sea contrasts, and with reentrant boundary conditions—a cloud that exits the domain on one side reenters on the other side.

The clouds' spontaneous organization via internal feedbacks appears to be related to the interaction of clouds with their near environment. Researchers have put forward four feedback mechanisms to explain self-aggregation: radiative processes, entrainment at the edge of clouds, cold pools, and waves.[2]

All the aggregation feedbacks work in a similar fashion: They favor the formation of clouds in regions near clouds and disfavor formation in regions devoid of them. Both actions are positive feedbacks because they reinforce an existing cloud distribution. More clouds form where there are more clouds, and fewer form where there are fewer. That reinforcement leads to a spatial separation between cloudy, moist regions and non-cloudy, dry ones.

In radiative feedback, dry regions are associated with strong radiative cooling to space because of their relatively small amount of atmospheric water vapor. It is similar to a local greenhouse effect, in that water vapor acts as a greenhouse gas—less water vapor means fewer greenhouse gases and thus cooling. That cooling of the air triggers it to subside and flow in a diverging pattern near Earth's surface. Because most water vapor is located there, the relatively dry subsiding air from above

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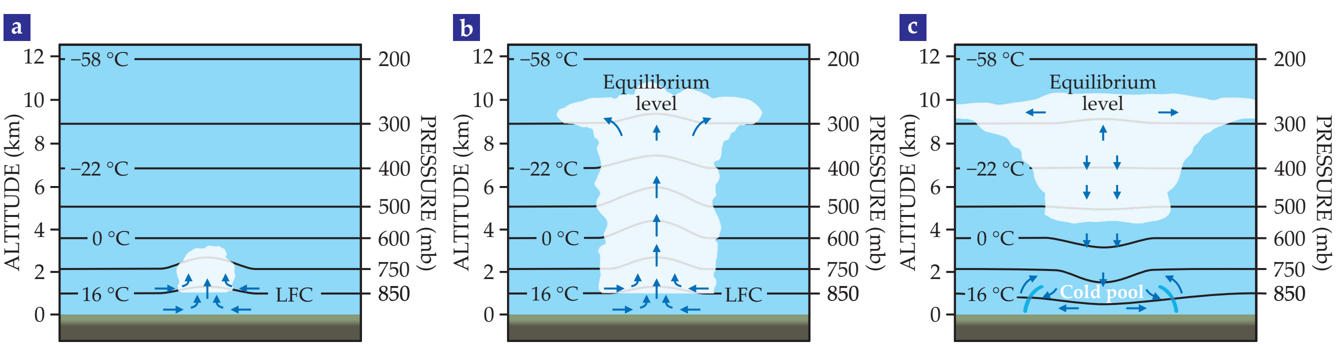

FIGURE 1. CONVECTIVE-CLOUD LIFE CYCLE. During a storm's developing stage **(a)**, air starts rising, and when it reaches its level of free convection (LFC), it becomes buoyant. **(b)** It keeps rising until, at the cloud's mature stage, it reaches the equilibrium level, where its density matches that of the surrounding air. **(c)** The upper-level air then spreads horizontally, forming what's known as an anvil cloud. Liquid and ice droplets grow through microphysical processes and begin to fall toward the ground. In the dissipating stage, the partial evaporation of the precipitating condensates produces a mass of cooler air and generates a downdraft that spreads it horizontally at the surface. (Adapted from the COMET website at http://meted.ucar.edu of the University Corporation for Atmospheric Research, sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration, US Department of Commerce. ©1997–2023 UCAR.)

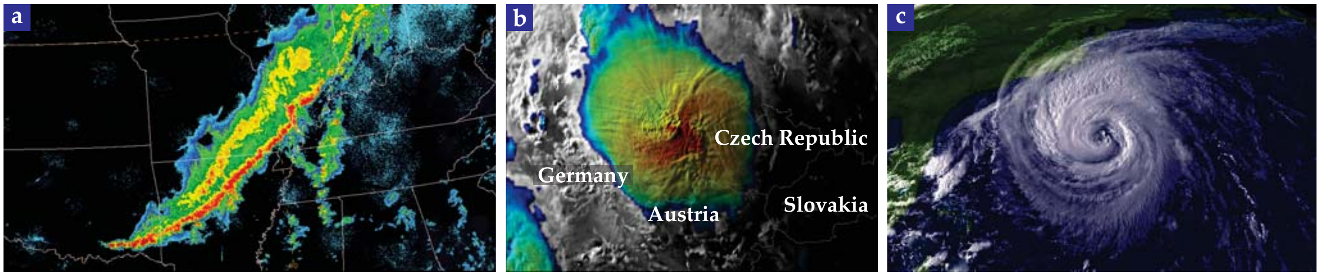

FIGURE 2. MESOSCALE CONVECTIVE SYSTEMS are storms in the atmosphere that can span hundreds of kilometers. Some examples include **(a)** squall lines, which are a type of elongated multicloud structure; **(b)** a circular multicloud structure; and **(c)** a tropical cyclone, composed of a rotating multicloud structure. (Panel a courtesy of Nolan Atkins; panel b © EUMETSAT 2011; panel c courtesy of the World Meteorological Organization.)

replaces the relatively moist near-surface air, drying that part of the atmosphere further. The drier air is less buoyant and thus less receptive to convection and cloud formation.[3,4]

With entrainment feedback, as air rises and water vapor condenses to form a cloud, air viscosity causes the rising air to drag surrounding air with it. The edge of the cloud becomes highly turbulent and leads to the entrainment and the mixing of environmental air with the cloudy air. Mixing at the edge can significantly reduce cloud buoyancy if the entrained air is dry. Indeed, dry-air mixing will lead to the evaporation of some of the cloud droplets, and the concomitant latent cooling reduces the cloud buoyancy. Conversely, if the environmental air is moist, which would happen if a cloud formed near a recently formed one, the upward motion will not be arrested, and it'll form more easily. That possibility favors the clustering of clouds in the moistest region.[5]

In cold-pool feedback, as cold pools spread at the surface below a precipitating cloud, they raise the surrounding warmer air at the edges. The mechanically induced upward motion encourages the formation of new clouds near the edge of cold pools. And by facilitating new clouds in the vicinity of existing ones, cold pools thus reinforce the clustering of clouds in space.[6]

In wave feedback, convection triggers internal gravity waves that propagate in stratified media.[7] (For more on internal gravity waves, see the article by Callum Shakespeare, Physics Today, June 2019, page 34.) Suppose that the atmosphere is a two-layer fluid: The denser, bottom layer of air ranges from the ground to the bases of the clouds at an altitude of about 1 km, and the lighter layer above spans from the clouds' bases to their tops at an altitude of about 10 km. In that simplified case, internal waves become interfacial waves that propagate between the two layers, similar to surface waves between air and water when a rock is thrown in a pond. Interfacial waves between the two layers are triggered by convection and propagate away from the clouds. The waves can form standing wavepackets that separate convectively active areas from inactive ones.[8]

Because of the idealized settings in which self-aggregation is investigated, researchers are still debating its relevance to the real world. Ending that debate will require more observations, either from satellites or *in situ* measurements. With recent improvements to the fundamental understanding of the physical processes involved in self-aggregation, researchers should be positioned to identify each feedback in observations and determine to what extent each dominates in the real atmosphere.

Squall lines formed by wind shear

The difficulty in studying realistic settings from observations is that in addition to internal feedbacks, the interaction of clouds with the atmosphere's large-scale flow can contribute to organizing convection. An important example of such an interaction occurs in squall lines, known to emerge in the presence

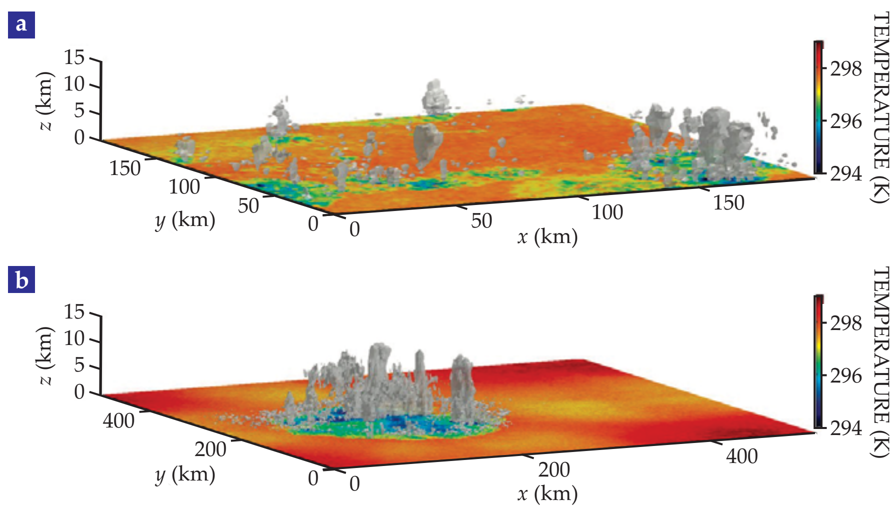

FIGURE 3. IDEALIZED NUMERICAL SIMULATIONS. In the absence of feedback mechanisms, **(a)** simulated clouds appear disorganized in space. **(b)** Under the influence of those mechanisms, however, clouds can self-aggregate into a coherent convective structure, and that behavior increases with domain size and temperature. Self-aggregation is associated with a large-scale drying of the atmosphere and enhanced large-scale outgoing radiative cooling to space. Based on observations of relative humidity, researchers have learned that the middle troposphere is consistent with modeled self-aggregation and is on average drier for an atmosphere in which the same amount of precipitation is concentrated into a small number of convective clusters. (Adapted from ref. 1.)

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> “Observing convective organization and the relevant physical processes is challenging.”

of vertical wind shear—that is, when wind at the surface moves at a different speed than wind at altitude. In addition, large-scale variations can be induced by atmospheric circulations in the tropics. (For more on tropical circulation, see the article by Thomas Birner, Sean Davis, and Dian Seidel, Physics Today, December 2014, page 38.)

The theoretical explanation for the development of squall lines came from a foundational paper published 35 years ago.[9] It describes how wind shear can interact with the cold pool, which in this case plays a key role in maintaining the storm. The interaction is based on three main principles, shown schematically in figure 4.

First, wind shear blocks the spread of the cold pool from where it originates. Second, the cold pool acts as a ramp that lifts the warm and moist air. Finally, wind shear and the cold pool together produce a vorticity dipole—the two counterrotating wind profiles, often indicated with a + sign and a – sign.

The vorticity dipole supports upward motion between the wind profiles, which accelerate the upward motion and promote deep vertical convection. The edge of the cold pool then becomes an optimal spot for deep convective updrafts that lead to cloud formation, precipitation, and squall lines. In other words, the storm precipitation feeds the cold pool, which maintains the conditions that favor the storm updraft and subsequent precipitation. The series of interactions allows squall lines to last as long as 24 hours and to travel for thousands of kilometers.

Intuitively, one would expect the coupling between the wind shear and the cold pool to depend on the shear intensity. When it’s too weak, as illustrated in figure 5a, there’s no particular interaction and therefore no organization of the deep clouds. When the shear increases, however, a squall line tends to develop perpendicular to the imposed wind, as seen in figure 5b, which corresponds to a horizontal wind variation of about 10 m/s over the 1 km layer closest to Earth’s surface. Beyond wind speeds of 10 m/s, squall lines are oriented at an angle less than 90 degrees to the wind direction, as shown in figure 5c.

Many researchers have studied the angle of orientation of squall lines. A recent numerical simulation analysis,[10] for example, validated a decades-old hypothesis[11] that suggested that the orientation of squall lines reduces incoming wind shear and restores the equilibrium between wind shear and cold-pool spreading. Indeed, subsequent findings have indicated that cold-pool intensity is largely insensitive to wind shear, and the optimal value of shear is the one that matches the strength of cold-pool spreading. In other words, the orientation of the squall line preserves the organization of convection even in the presence of a strong shear greater than the optimal value.

Wind shears with intensities up to the optimal value make squall lines more organized and, therefore, can drive their intensification. Recent climate-model simulations, for example, highlight that over the Sahel region in north-central Africa changing wind shear is the main reason for the enhancement of squall lines under warming conditions.[12] That case illustrates how wind shear adds a critical contribution to the intricate

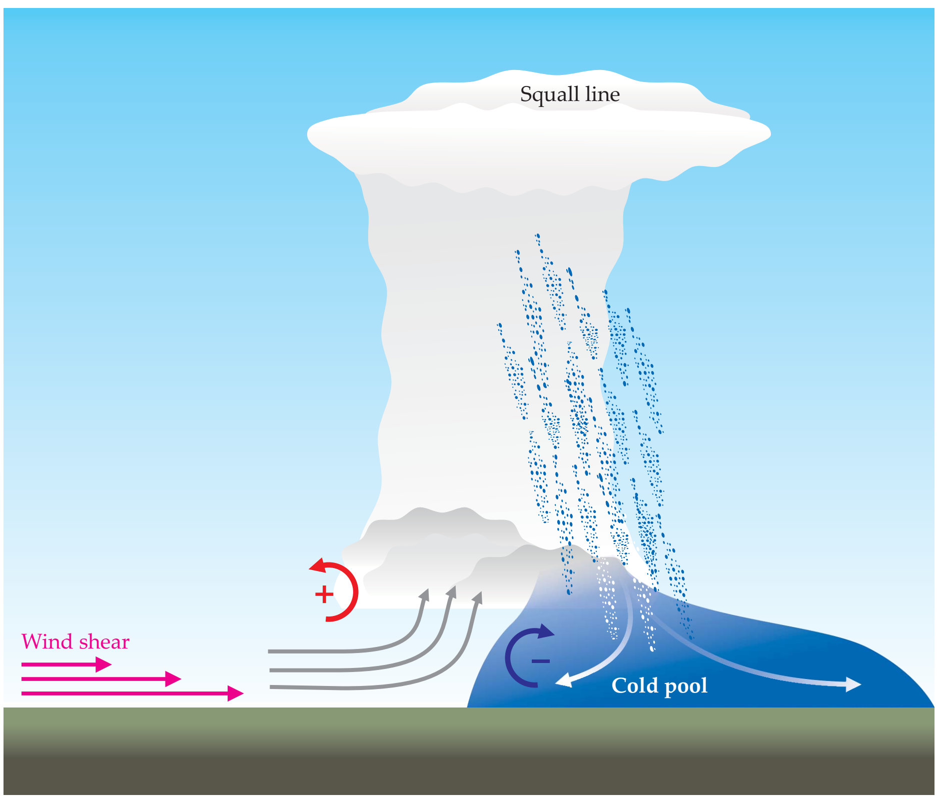

FIGURE 4. SEVERAL INTERACTIONS lead to the formation of a squall line of clouds. Rain and its subsequent evaporation fuel the rise of a mass of cold air that spreads below a cloud. Incoming wind (gray arrows) blocks the spreading of the cold pool, which in turn acts as a ramp for raising moist warm air. The vertical variation of wind strength (pink arrows) induces a positive vorticity (red plus sign). That twisting motion interacts with the negative vorticity found in the cold pool (blue minus sign), which favors storm drafts and other upward motion that promotes the formation of squall lines in the atmosphere.

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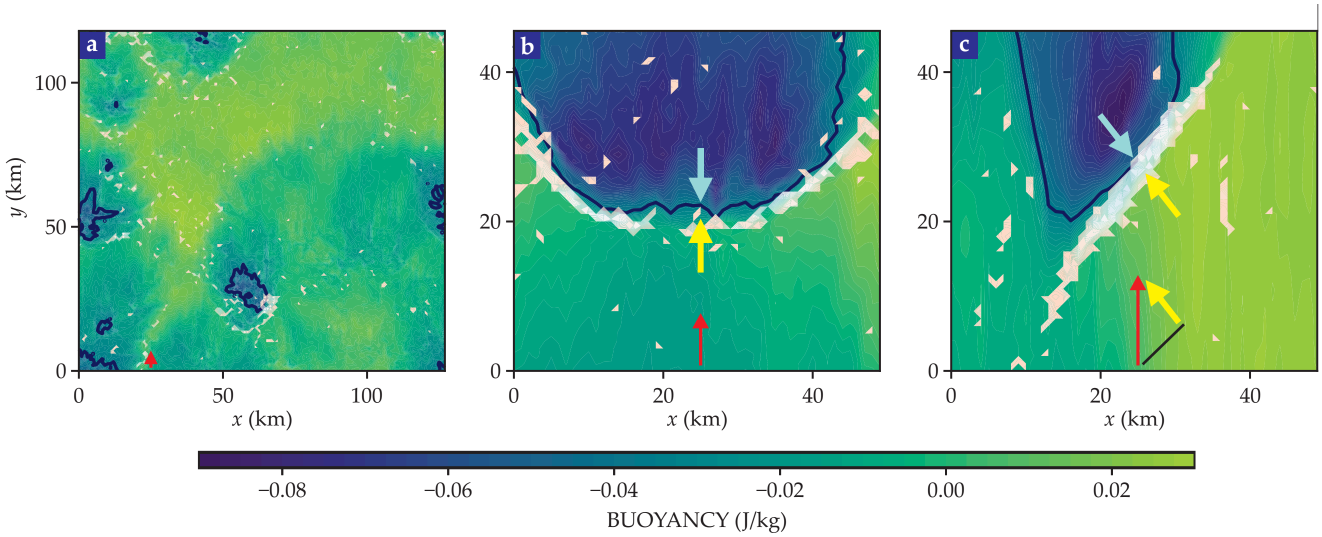

FIGURE 5. WIND SHEAR influences the orientation of tropical squall lines. In each of the three simulation cases, the color denotes the buoyancy field, which is proportional to the atmosphere's anomalous temperature relative to the climatological average. The cloud locations are shown in white. **(a)** When no shear is imposed, no organization of a squall line is observed. **(b)** For a horizontal wind speed $U = 10$ m/s (red arrow), a squall line of clouds develops perpendicular to the wind direction, and the projected shear (yellow arrow) is optimal because it balances the force from the spreading of the atmospheric cold pool (blue arrow). **(c)** For $U = 20$ m/s, which corresponds to greater than the optimal shear, the squall line is oriented at an acute angle to the wind direction. In that case, the squall line's orientation reduces the projected shear so as to restore the force balance with the cold pool. (Adapted from ref. 10.)

relationship between climate change and the degree of deep-convection organization.

The road ahead

Researchers don't know the extent to which internal feedbacks organize clouds in the real atmosphere compared with large-scale forcings, such as wind shear and land–ocean contrasts. The response of clouds to global warming is one of the largest uncertainties in current predictions of climate change from models (see the article by Tapio Schneider, Nadir Jeevanjee, and Robert Socolow, Physics Today, June 2021, page 44). Given the dependence of cloud cover on convective organization, how convection changes with climate change is of major importance. All the aforementioned idealized studies can help address those uncertainties in observations and shed new light into the physical processes at stake in the atmosphere. That combination of idealized studies with analysis of real-world data will help researchers determine how cloud organization may change with global warming.

Observing convective organization and the relevant physical processes is challenging. For instance, assessing the radiative feedback requires sensitive measurements of radiative cooling rates close to the surface, which are difficult to obtain from satellite measurements.[13] The recent international observational campaign EUREC^{4}A provided invaluable *in situ* data of vertically resolved radiative cooling rates.[14] Those data helped researchers develop a theoretical basis for what dictates low-level cooling rates,[15] notably their close relationship with water-vapor variations.

A global climatology of cold pools is also missing, as they are equally challenging to observe from satellites. Recent work using synthetic-aperture radar and machine learning to obtain images shows some promise.[16] The European Space Agency's new Earth Explorer mission, Harmony, will provide fine-resolution measurements of near-surface winds.[17] Those observations will undoubtedly contribute to improved measurements and understanding of cold-pool properties.

A recent study attributed the latest observed trend of precipitation extremes to changes in convective organization.[18] Accurate predictions of the hydrological cycle, therefore, will require researchers to better understand convective organization and how it will change with warming. The theoretical work discussed in this article, increased and improved observational data, and new methodologies that include machine-learning approaches have tremendously increased the scientific basis to answer that important question. All the promising avenues make it an exciting time for cloud research.

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