transmitted by quantum mechanical fluctuations that radiate out from each particle (see the figure). In two dimensions these fluctuations decay more slowly with distance, resulting in stronger interactions. The fluctuations also become more intense near a quantum phase transition. Many of the superconductors discovered in the past decade are indeed layered compounds close to a quantum phase transition (*6*, *7*).

Rather than using direct chemical synthesis, Shishido *et al*. turn to a method used commonly to fabricate semiconductor devices—molecular beam epitaxy (MBE), a technique involving the direct deposition of atoms from an atomic beam onto a substrate, slowly building an ordered crystal, layer by layer (*8*, *9*). They apply the MBE method to a class of strongly correlated metals called heavy-fermion compounds, materials that contain arrays of rare earth atoms that trap electrons tightly inside f orbitals where they experience strong interactions ("heavy fermion" refers to the very large effective mass of the charge carriers in these metals).

Shishido *et al*. start with a three-dimensional heavy-fermion compound, CeIn$_3$. In three dimensions, the f electrons in this material are localized and arrange their magnetic properties to form an antiferromagnet. Earlier experiments showed that under high pressure (*4*), the magnetism could be suppressed, driving the material to a quantum critical point where superconductivity developed. Layered derivatives of this material in which the magnetism was sometimes absent and superconductivity developed spontaneously were later discovered (*6*). Could one systematically reproduce these effects using MBE methods?

By successfully identifying the conditions and substrate needed to lay down layers of heavy-electron material, Shishido *et al*. systematically lower the dimensionality of CeIn$_3$. They do this by introducing alternating layers of magnetic CeIn$_3$ and nonmagnetic LaIn$_3$, which is a weakly interacting metal. They have prepared a family of such compounds containing variable thicknesses of cerium layers. With eight cerium layers the material behaved like three-dimensional CeIn$_3$, with a magnetic phase transition, but as they reduced the number of cerium layers, they found that the reduced dimensionality suppressed the temperature of the magnetic phase transition, driving it to absolute zero (0K) by the time they had reached the two-layer system.

Two fascinating properties developed in the two-layer system, suggesting that it lies right at a quantum phase transition. First, Shishido *et al*. found that the resistance of this material is very sensitive to magnetic fields, an indication of scattering of electrons off the soft magnetic fluctuations around a magnetic quantum phase transition. Second, the temperature ($T$) dependence of the resistivity changed qualitatively as the dimensionality of the crystal decreased, shifting from a $T^2$ dependence expected in conventional metals to a linear dependence on temperature—behavior characteristic of inelastic scattering off spin fluctuations.

These experiments are a milestone in the application of MBE methods to layered intermetallic materials, showing that these methods can be successfully used to tune the dimensionality and increase the electron interactions in these kinds of materials. Although the current experiments did not observe any emergent superconductivity at the magnetic quantum phase transition, this next milestone may not be far away. In the current samples, the resistivity of the most two-dimensional samples is large, an effect the authors attribute to interdiffusion of lanthanum and cerium between layers (*3*). The scattering this creates is well known to break up the electron pairs needed for superconductivity. Future experiments, replacing the lanthanum with smaller transition metal ions, may well be able to solve this problem.

### References and Notes

1. W. P. McCray, *Nat. Nanotechnol.* **4**, 2 (2009).
2. See, e.g., http://en.wikipedia.org/wiki/High-temperature_superconductivity.
3. H. Shishido *et al.*, *Science* **327**, 980 (2010).
4. N. D. Mathur *et al.*, *Nature* **394**, 39 (1998).
5. P. Coleman, A. J. Schofield, *Nature* **433**, 226 (2005).
6. J. L. Sarrao, J. D. Thompson, *J. Phys. Soc. Jpn.* **76**, 051013 (2007).
7. H. Hosono *et al.*, *N. J. Phys.* **11**, 025003 (2009).
8. M. B. Panish, *Science* **208**, 916 (1980).
9. B. A. Joyce, *Rep. Prog. Phys.* **48**, 1637 (1985).
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ATMOSPHERIC SCIENCE

# Can We Understand Clouds Without Turbulence?

Advances at the interface between atmospheric and turbulence research are helping to elucidate fundamental properties of clouds.

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Just over 50 years ago, Henry Houghton published an essay in *Science* entitled "Cloud physics: Not all questions about nucleation, growth, and precipitation of water particles are yet answered" (*1*). Since then, understanding of cloud processes has advanced enormously, yet we still face some of the basic questions Houghton drew attention to. The interest in finding the answers, however, has steadily increased, largely because clouds are a primary source of uncertainty in projections of future climate (*2*). Why is our understanding of cloud processes still so inadequate, and what are the prospects for the future?

Clouds are dispersions of drops and ice particles embedded in and interacting with a complex turbulent flow. They are highly nonstationary, inhomogeneous, and intermittent, and embody an enormous range of spatial and temporal scales. Strong couplings across those scales between turbulent fluid dynamics and microphysical processes are integral to cloud evolution (see the figure).

Turbulence drives entrainment, stirring, and mixing in clouds, resulting in strong fluctuations in temperature, humidity, aerosol concentration, and cloud particle growth and decay (*3*). It couples to phase transition processes (such as nucleation, condensation, and freezing) as well as particle collisions and breakup (*4*). All these processes feed back on the turbulent flow by buoyancy and drag forces and

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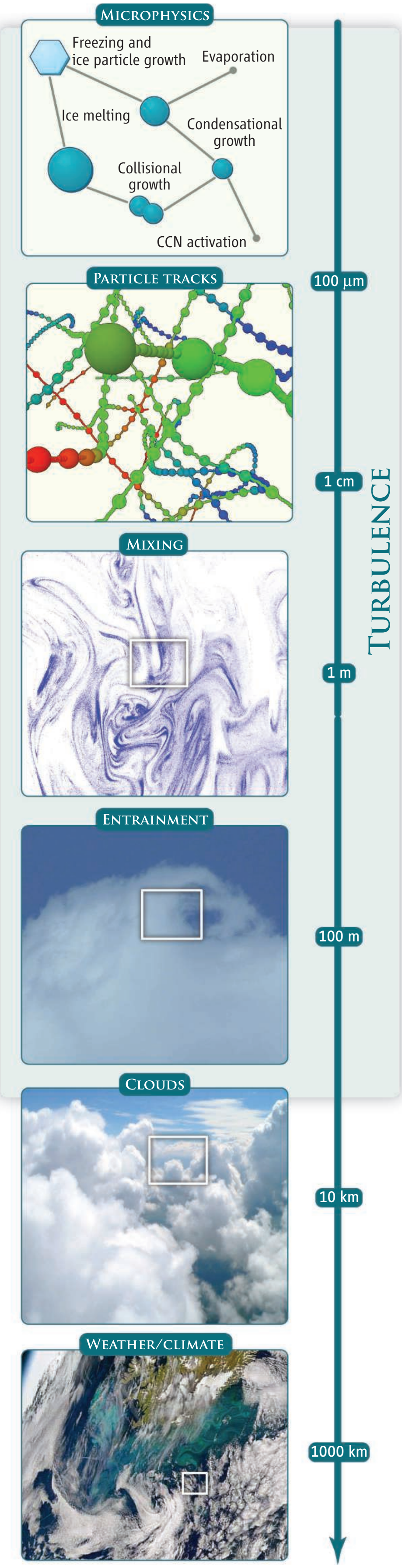

**A matter of scale.** Turbulence on scales from hundreds of meters to fractions of millimeters affects the formation and dynamics of clouds, with consequences extending to the scale of weather and global climate. CCN, cloud condensation nuclei.

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affect cloud dynamical processes up to the largest scales (*5*–*7*).

To a large extent, understanding of clouds has come through the study of two phenomena: cloud microphysical processes in nonturbulent fluids, and large-scale cloud circulation and dynamics. At the same time, understanding of the physics of fully developed turbulent flows has advanced rapidly. For example, sophisticated laboratory apparatus now allows the study of nucleation and growth of cloud particles under well-controlled conditions (*8*). Computational models ranging from the cloud to the global scale elucidate detailed interactions between aerosols and cloud dynamics (*9*). And three-dimensional particle tracking and fully resolved turbulence simulations have substantially advanced our understanding of turbulent transport and mixing (*10*).

The frontier in cloud physics, and the challenge in understanding cloud processes, lies at the intersection of these two fields (*11*). For example, high-resolution measurements of temperature, liquid water content, aerosol properties, and airflow reveal fascinating small-scale cloud structures, invisible with earlier technology (*3*, *12*). Laboratory experiments and numerical simulations are providing detailed information on cloud microphysics (*8*), turbulent dynamics (*13*), and interactions and collisions between droplets (*14*, *15*). Scale-resolving simulations that merge methods from the cloud and turbulence communities are elucidating the wide variety of circulation regimes (*16*). These tools allow the full complexity of microphysical and fluid-dynamical interactions in clouds to be explored (see the figure).

Two examples illustrate this further. First, computational, laboratory, and field studies (*17*, *18*) have explored two fundamentally different regimes for the interplay between turbulent mixing and droplet growth and evaporation. At large scales, mixing occurs at sharp fronts and fields are inhomogeneous, whereas at small scales, mixing is smooth and homogeneous. These regimes strongly affect spatiotemporal droplet growth and evaporation, with implications for precipitation initiation and radiative properties of clouds.

Second, recent research has changed our understanding of rain formation. Rain formation has long been attributed to collisions and subsequent coalescence resulting from cloud particles falling at different terminal speeds in a quiescent fluid. This view neglected the fact that clouds are turbulent. Turbulence provides a random acceleration term to compete with the gravitational sedimentation, resulting in complex particle trajectories that cross fluid streamlines and lead to spatially clustered particle distributions (see the figure). This process substantially enhances collision rates, thus reducing the time required to form precipitation in clouds (*15*, *19*).

With these advances we can better address some of Houghton's persistent questions (*1*). Laboratory facilities are being developed for studying droplet activation, ice nucleation, and condensational growth in flows with realistic turbulence and thermodynamics conditions. Lagrangian particle tracking can elucidate cloud particle dynamics in the laboratory as well as in real clouds. Scale-resolving numerical simulations have begun to capture the interplay of turbulent mixing and nonlinear phase transitions. The resulting insights will enable the development of hierarchies of models for predicting how small-scale processes couple to the larger scales and how this coupling affects weather and climate.

### References and Notes

1. H. G. Houghton, *Science* **129**, 307 (1959).
2. J. Heintzenberg, R. J. Charlson, Eds., *Clouds in the Perturbed Climate System* (MIT Press, Cambridge, MA, 2009).
3. H. Siebert *et al.*, *Bull. Am. Meteorol. Soc.* **87**, 1727 (2006).
4. R. A. Shaw, *Annu. Rev. Fluid Mech.* **35**, 183 (2003).
5. B. Stevens *et al.*, *Mon. Weather Rev.* **133**, 1443 (2005).
6. I. M. Held, M. Zhao, B. Wyman, *J. Atmos. Sci.* **64**, 228 (2007).
7. C. Stan *et al.*, *Geophys. Res. Lett.* **37**, L01702 (2010).
8. F. Stratmann, O. Moehler, R. Shaw, H. Wex, in *Clouds in the Perturbed Climate System*, J. Heintzenberg, R. J. Charlson, Eds. (MIT Press, Cambridge, MA, 2009), pp. 149–172.
9. B. Stevens, G. Feingold, *Nature* **461**, 607 (2009).
10. F. Toschi, E. Bodenschatz, *Annu. Rev. Fluid Mech.* **41**, 375 (2009).
11. Z. Warhaft, *Fluid Dyn. Res.* **41**, 011201 (2009).
12. K. E. Haman, S. P. Malinowski, M. J. Kurowski, H. Gerber, J.-L. Brenguier, *Q. J. R. Meteorol. Soc.* **133**, 213 (2007).
13. M. Bourgoin *et al.*, *Science* **311**, 835 (2006).
14. J. Chun, D. L. Koch, S. L. Rani, A. Ahluwalia, L. R. Collins, *J. Fluid Mech.* **536**, 219 (2005).
15. L.-P. Wang, O. Ayala, B. Rosa, W. W. Grabowski, *N. J. Phys.* **10**, 075013 (2008).
16. O. Pauluis, J. Schumacher, *Comm. Math. Sci.* **8**, 295 (2010).
17. K. Lehmann, H. Siebert, R. A. Shaw, *J. Atmos. Sci.* **66**, 3641 (2009).
18. S. P. Malinowski *et al.*, *N. J. Phys.* **10**, 075020 (2008).
19. M. Pinsky, A. Khain, H. Krugliak, *J. Atmos. Sci.* **65**, 357 (2008).
20. We thank O. Moehler, J. Schumacher, H. Siebert, and B. Stevens for important comments.

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