New research adds to work of Prandtl, father of modern aerodynamics

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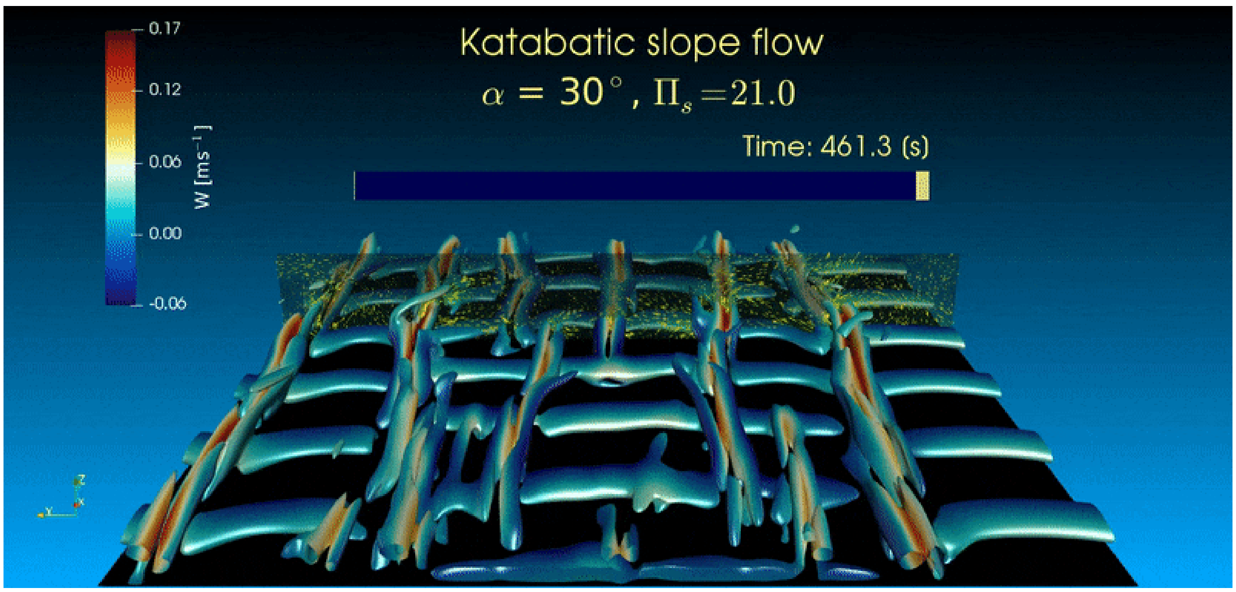

Contour visualization of the mixed-mode instabilities in the Prandtl model for a slope angle of 30 (deg). Flow is from top to bottom. Vortical structures are identified using the Q-criterion. Credit: Inanc Senocak

In 1942, Ludwig Prandtl—considered the father of modern aerodynamics—published "Führer durch die Strömungslehre," the first book of its time on fluid mechanics and translated to English from the German language in 1952 as "Essentials of Fluid Mechanics." The book was uniquely successful such that Prandtl's students continued to maintain and develop the book with new findings after his death. Today, the work is available under the revised title "Prandtl—Essentials of Fluid Mechanics," as an expanded and revised version of the original book with contributions by leading researchers in the field of fluid mechanics.

Over the years, the last three pages of Prandtl's original book, focusing on mountain and valley winds, have received some attention from the meteorology research community, but the specific pages have been largely overlooked by the fluid mechanics community to the point that the content and the exact mathematical solutions have disappeared in the current expanded version of the book. But today in the age of supercomputers, Inanc Senocak, associate professor of mechanical engineering and materials science at the University of Pittsburgh Swanson School of Engineering, is finding new insights in Prandtl's original work, with important implications for nighttime weather prediction in mountainous terrain.

Drs. Senocak and Cheng-Nian Xiao, a postdoctoral researcher in Dr. Senocak's lab, recently authored a paper titled "Stability of the Prandtl Model for Katabatic Slope Flows," published in the *Journal of Fluid Mechanics*. The researchers used both linear stability theory and direct numerical simulations to uncover, for the first time, fluid instabilities in the Prandtl model for katabatic slope flows.

Katabatic slope flows are gravity-driven winds common over large ice sheets or during nighttime on mountain slopes, where cool air flows downhill. Understanding those winds are vital for reliable weather predictions, which are important for air quality, aviation and agriculture. But the complexity of the terrain, the stratification of the atmosphere and fluid turbulence make computer modeling of winds around mountains difficult. Since Prandtl's model does not set the conditions for when a slope flow would become turbulent, that deficiency makes it difficult, for example, to predict weather for the area around Salt Lake City in Utah, where the area's prolonged inversions create a challenging environment for air quality.

"Now that we have more powerful supercomputers, we can improve upon the complexity of the terrain with better spatial resolutions in the mathematical model," says Dr. Senocak. "However, numerical weather prediction models still make use of simplified models that have originated during a time when computing power was insufficient."

The researchers found that while Prandtl's model is prone to unique fluid instabilities, which emerge as a function of the slope angle and a new dimensionless number, they have named the stratification perturbation parameter as a measure of the disturbance to the background stratification of the atmosphere due to cooling at the surface. The concept of dimensionless numbers, for example the Reynolds number, plays an important role in thermal and fluid sciences in general as they capture the essence of competing processes in a problem.

An important implication of their finding is that, for a given fluid such as air, dynamic stability of katabatic slope flows cannot simply be determined by a single dimensionless parameter alone, such as the Richardson number, as is practiced currently in the meteorology and fluids dynamics community. The Richardson number expresses a ratio of buoyancy to the wind shear and is commonly used in weather prediction, investigating currents in oceans, lakes and reservoirs, and measuring expected air turbulence in aviation.

"An overarching concept was missing, and the Richardson number was the fallback," says Dr. Senocak. "We're not saying the Richardson number is irrelevant, but when a mountain or valley is shielded from larger scale weather motions, it doesn't enter into the picture. Now we have a better way of explaining the theory of these down-slope and down-valley flows."

Not only will this discovery be important for agriculture, aviation and weather prediction, according to Dr. Senocak, but it will also be vital for climate change research and associated sea-level rise, as accurate prediction of katabatic surface wind profiles over large ice sheets and glaciers is critical in energy balance of melting ice. He notes that even in the fluids dynamics community, the discovery of this new surprising type of instability is expected to arouse a lot of research interest.

Next, Dr. Senocak is advising and sponsoring a senior design team to see if researchers can actually observe these fluid instabilities in the lab at a scale much smaller than a mountain.

More information: Cheng-Nian Xiao et al, Stability of the Prandtl model for katabatic slope flows, *Journal of Fluid Mechanics* (2019). DOI: 10.1017/jfm.2019.132

Provided by University of Pittsburgh

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