KUO-NAN LIOU, 1943–2021

Kuo-Nan Liou passed away on March 20, 2021. Liou was a distinguished professor in the Department of Atmospheric and Oceanic Sciences and the founding director of the Joint Institute for Regional Earth System Science and Engineering at the University of California, Los Angeles (UCLA). Before joining UCLA in 1997, he was a professor at the University of Utah for 22 years.

Liou received his B.S. and Ph.D. degrees from National Taiwan University and New York University in 1965 and 1968, respectively. He had a distinguished career, and his honors include membership in the U.S. National Academy of Engineering, the status of Academician of Academia Sinica, and foreign membership in the Chinese Academy of Sciences. Liou received numerous awards, including the AMS Jule G. Charney Medal, the AMS Carl-Gustaf Rossby Research Medal, the Biennial William Nordberg Medal from the Committee on Space Research, the International Radiation Commission Quadrennial Gold Medal, the Roger Revelle Medal from the American Geophysical Union (AGU), and inclusion in the Nobel Peace Prize bestowed on the Intergovernmental Panel on Climate Change (IPCC) in 2007. He was a Fellow of AMS, AGU, the American Association for the Advancement of Science, and the Optical Society of America.

Liou made seminal contributions to atmospheric science and education/mentoring, with a focus on atmospheric radiation, light scattering, remote sensing, and cloud/aerosol radiative forcing effects on the climate system.

Accomplishments in Atmospheric Research

As praised by Warren Wiscombe, the former chief scientist of the Atmospheric Radiation Measurement (ARM) Program of the U.S. Department of Energy, Liou was one of those pioneering researchers who demonstrated that atmospheric radiation should no longer be consigned to the fringes of meteorology but instead should take a central place in the new world of climate science. Liou moved the field forward with a quantum leap through his work on the theory of radiative transfer, the investigation of radiative effects of clouds and aerosols, and the development of methods for inferring atmospheric and surface parameters through remote sensing.

The importance of clouds in atmospheric radiation is evident, since they cover 60%–70% of the globe. Liou presented a monograph, *Radiation and Cloud Processes in the Atmosphere: Theory, Observation, and Modeling,* which integrates radiative transfer and cloud physics coherently, bridges the gap between radiation and climate processes in clouds, and discusses important topics in radiation, cloud physics, thermodynamic equilibrium, and simple climate models. The contents of this volume are closely related to the successful development of climate models for the investigation of global climate change and remote sensing techniques for the inference of cloud and aerosol properties. In his well-known 1986 paper “Influence of Cirrus Clouds on Weather and Climate Processes: A Global Perspective,” Liou demonstrated that cirrus clouds are ubiquitous, particularly in the tropics, and are critical elements for the understanding of the global energy budget and water cycle. Their effect on climate was illustrated through a hierarchy of climate models with varying degrees of complexity. Since the publication of this paper, numerous field experiments have been undertaken to collect data to quantify the impact of cirrus on the Earth's radiation budget and climate.

In the area of light scattering research, the work by Liou and James Hansen may be the first study that systematically compares the geometric optics method and Lorenz–Mie theory. The scattering of light by spheres can be solved by the exact Lorenz–Mie theory and computation can be performed accordingly. However, ice clouds in the atmosphere are composed almost exclusively of nonspherical ice crystals such as solid and hollow columns, plates, bullet rosettes, aggregates, and dendrites. Also, ice particles have surfaces with varying degrees of roughness. An exact solution for light scattering by nonspherical ice crystals covering all sizes from the Rayleigh to geometric optics regimes does not exist in practical terms.

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In the early 1970s, Liou was the first to pursue the study of cirrus cloud radiative properties by considering nonspherical ice crystals. He was the first who developed the theoretical basis for the depolarization of the backscattered signal from nonspherical ice particles with a linearly polarized laser beam. This work established the basis for the cloud phase detection using ground-based, airborne, or spaceborne lidar. In the 1980s, Liou pioneered the study of the scattering of polarized light by nonspherical ice crystals by means of the principle of geometric optics. In the 1990s, Liou and one of his students developed an innovative physical-geometric optics method that is often referred to as the improved geometric optics method (IGOM) for light scattering by large particles. The IGOM substantially overcame the shortcomings of the conventional geometric optics method for light scattering; in particular, the IGOM for the first time was able to depict the variation of the extinction efficiency with particle size within the geometric optics framework, and it overcame the inherent singularity, referred to as the delta-transmission, which is associated with the ray-tracing technique for a particle with parallel surface facets.

The IGOM and its subsequent developments in a synergistic combination with other methods (e.g., the finite-difference time domain method or the invariant imbedding T-matrix method) for small-to-moderate particles provide advanced modeling capabilities for cirrus cloud optical property computations for downstream applications, as summarized in a research volume, *Light Scattering by Ice Crystals,* written by Liou and the former student. In particular, the advanced light-scattering computational capabilities provided ice cloud optical property models for remote sensing implementations such as the NASA MODIS (Moderate Resolution Imaging Spectroradiometer), CERES (Clouds and the Earth's Radiant Energy System), and AIRS (Atmospheric Infrared Sounder) operational ice cloud property retrieval products. The computations laid the foundation for fundamental datasets for ice cloud radiation parameterization schemes used in many climate models and for radiance simulations under ice-cloudy conditions in radiative transfer models, such as the well-known libRadtran developed by German scientists and the Community Radiative Transfer Model, a flagship effort of the NOAA Joint Center for Satellite Data Assimilation to facilitate forward radiative transfer simulations in remote sensing implementations. These advancements in simulating the optical properties of ice clouds would not have been possible without Liou's pioneering work in this regard. Although he was a theorist, Liou also pursued light-scattering and cloud-physics laboratory experiments, primarily to test the theory. Liou's effort in the area of light scattering was recognized through a Creativity Award from the Atmospheric Sciences Division of the National Science Foundation for "Light Scattering by Ice Crystals: Theory and Experiment," which he received in 1996.

In his landmark book, the late Nobel Laureate Chandrasekhar presented the subject of radiative transfer in plane-parallel (1D) atmospheres as a branch of mathematical physics and developed numerous solution methods and techniques. In his early career, Liou followed the discrete-ordinates method developed by Chandrasekhar and in 1974 derived for the first time the analytic solution for the four-stream approximation for radiative transfer. On the basis of the delta-four-stream approach, Liou and one of his former students constructed an efficient spectral radiative transfer model, referred to as the Fu–Liou radiative transfer model, which includes the correlated *k*-distribution method for the sorting of nongray gaseous absorption in scattering atmospheres and the scattering and absorption properties of hexagonal ice particles. Since its inception in early 1990s, the Fu–Liou code has been used as a standard broadband radiative transfer model to study climate forcing effects of clouds and aerosols, and it has been employed by NASA for the retrieval of satellite-observed atmospheric and surface radiative energy fluxes. The Fu–Liou code was further developed and coupled with the widely used Weather Research and Forecasting (WRF) model by Liou and an associate, referred to as the Fu–Liou–Gu module in the officially released WRF model since 2012. Although not widely noted, Liou proved the equivalence of the principle of invariance for finite atmospheres and the adding method for radiative transfer. We call special attention to the work of Liou and a former student on the fundamental physics associated with the correlated *k*-distribution method used for an inhomogeneous atmosphere. In particular, they demonstrated that two correlated conditions are necessary and sufficient for the exact transformation of the wavenumber integration to an integration over the cumulative probability function space. They further developed an innovative approach to treat overlap absorption between H_2O and CO_2 lines in the correlated *k*-distribution framework. This study signifies a milestone contribution to accounting for nongray gaseous absorption in atmospheric radiative transfer.

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Liou was one of the pioneers in the development of 3D radiative transfer theories based on the finite spherical-harmonics expansion of the intensity and scattering phase function. In particular, he developed a successive order-of-scattering approach for 3D radiative transfer that has the advantage of applicability to intricate particle geometry. It also offers an innovative way of constructing a 3D cloud extinction coefficient field from satellite observations. This study corrected the conventional 1D approach to the evaluation of sunlight reflected and absorbed by clouds, which is essential to the discussion of the role of clouds/radiation in climate and climate change. In addition, Liou and his associates derived computationally efficient semianalytic solutions for 3D radiative transfer based on a delta-diffusion approximation for application to broadband flux and heating calculations in cloudy atmospheres. In the past decade, Liou and his associates worked on 3D radiative transfer over mountains for high resolution climate models with the goal of improving regional climate simulations by incorporating the 3D radiation configuration in mountains and snow-covered regions that are especially vulnerable to climate change and global warming.

The capability of a passive satellite sensor is largely limited to the mapping and retrieval of clouds and aerosols without the vertical information. Liou's interest in 3D radiative transfer led him to develop a remote sensing technique for the mapping and imaging of 3D inhomogeneous clouds. In the 1990s, technological advances led to the development of millimeter-wave radars, which can penetrate through clouds and enhance their study. With the incorporation of a Doppler component, the vertical cloud water content and particle size can be inferred from the backscattering reflectivity and velocity spectrum. Liou combined the satellite horizontal cloud mapping and the vertical cloud profile determined from collocated and coincident radar observations and constructed novel 3D inhomogeneous cloud fields in a mesoscale grid. He and his associates applied this methodology to data collected by the DOE's ARM Program, and the results were successfully verified from the particle size distribution derived independently from collocated and coincident measurements by aircraft optical probes. Liou's work was highlighted in a feature article, "Mapping the Frozen Sky: Study Looks at Clouds from Both Sides Now," published in *Science News* in June 2002.

Although temperature, humidity, clouds, and precipitation have been routinely observed or computed from satellite data, the atmospheric heating rate, which has been conventionally calculated by using a radiative transfer model, has not been directly measured by existing satellite radiometers. Liou and his collaborators deduced from the principle of radiative transfer that the infrared heating rate profile can be expressed by a Fredholm equation of the first kind, with the weighting function defined as the product of air density and transmittance in the rotational band of water vapor for vertical profiling and the spectral radiance observations made at a mean angle for conversion to fluxes.

Liou developed a 1D cloud–precipitation–climate model to investigate the potential link between the perturbed cloud particle size distributions and precipitation produced by greenhouse warming/air pollution. If more small particles are produced, precipitation could decrease, leading to an increase in cloud water. More cloud water in the atmosphere implies more reflection of sunlight, leading to cooling and a potential offset of the warming produced by greenhouse gases. A reduction of cloud particle size of about 1 μm in eastern North America has been observed as a result of anthropogenic pollution. Liou's discovery linking cloud particle size and precipitation in climate change is now referred to as the second indirect climate forcing in aerosol–cloud feedbacks.

Liou and his associates conducted numerical simulations involving the effects on precipitation of the increase of anthropogenic aerosols in China in the last 50 years employing the UCLA atmospheric GCM. They showed that increased aerosol optical depths in China led to a noticeable increase in precipitation in the southern part of China in July due to the cooling in midlatitudes and produced a precipitation pattern referred to as "north drought/south flooding" that has been frequently observed in China during the past 50 years. Moreover, black carbon and dust in China would heat the air column in the middle to high latitudes and tend to move the simulated precipitation toward the Tibetan Plateau. Being the first to use long-term satellite data and a comprehensive cloud model to study ice clouds, they also found compelling evidence that large quantities of ice nucleating particles (an important factor in the formation of ice clouds) are produced by human activities. Their finding about ice cloud formation by anthropogenic aerosols has rarely been considered in modern weather and climate models. Given the fact that ice clouds play a central role in severe weather and climate change, an adequate representation of this process is expected to significantly improve climate projections.

In addition to his accomplishments in radiative transfer, remote sensing, and climate applications, Liou contributed to the basic understanding of microphysics, radiation, and turbulence interactions in clouds. In particular, he and a former student constructed a 2D model to understand the evolution of cirrus clouds. This study represents the first effort to incorporate in a cirrus model all the pertinent physical processes involving ice crystal formation and radiative transfer in clouds, and particularly a second-order turbulence closure. Turbulence has a significant role in the formation and dissipation of cirrus clouds, and the use of the traditional eddy mixing theory is insufficient for simulating observed ice crystal size distributions. Without the inclusion of a physically based radiation process in the model, reliable ice water content cannot be generated.

Service to the Science Community

Liou was actively engaged in service to the science community throughout his career. He served on numerous national and international committees. To list a few, he served as chair of Section 12, Special Fields and Interdisciplinary Engineering, National Academy of Engineering (2008–10); chair of the AGU Atmospheric Sciences Section Fellows Committee (2013–14); chair of the AGU Roger Revelle Medal Committee (2017–20); chair of the 1986 International Radiation Symposium; chair of the AMS Committee on Atmospheric Radiation (1982–84); and chair-elect of the AMS Atmospheric Research Awards Committee (2021–22). Despite his very busy schedule, Liou reviewed many manuscripts for journals and research proposals for funding agencies. Moreover, he served as an editor for the *Journal of the Atmospheric Sciences* (1999–2005), guest editor for a special volume on clouds and radiation, *Journal of Geophysical Research* (1987), review editor for the IPCC Report (1998–99), and associate editor for the *Journal of Quantitative Spectroscopy and Radiative Transfer* (2011–21).

Achievements in Education/Mentoring

We would remiss if we just summarize Liou's groundbreaking scientific accomplishments and service to the science community without mentioning his contributions to atmospheric education and mentoring graduate students. Liou's iconic book, *An Introduction to Atmospheric Radiation*—which has been translated into Chinese, Russian, Japanese, and Arabic—has educated several generations of researchers in the disciplines of atmospheric radiation and remote sensing. Of particular note is that this book was the first to incorporate the subject of remote sensing into an atmospheric radiation text. Academician K. Kondratyev of the Russian Academy of Sciences wrote, "Liou's monograph is unconditionally useful and timely, successfully filling a gap in publications on radiation of the atmosphere. It will quickly find a readership among specialists in atmospheric physics." Indeed, this text was used by a number of universities for the teaching of the subject of atmospheric radiation, and is frequently referred to by research scientists in the areas of radiative transfer, light scattering, and remote sensing. The 2002 edition includes about 70% new material. Y. Yung of the California Institute of Technology commented, "Liou's book is broad and rigorous. It covers the topics well from fundamental principles to applications. A student who has mastered the book will be well prepared. A research worker who needs a quick review will find this an invaluable reference."

A large portion of Liou's legacy is reflected by the number and quality of the graduate students he trained. In total, he guided the completion of 33 doctoral dissertations in addition to many master's theses. Many of Liou's former students are prominent researchers in their respective research areas. In addition to his own graduate students, Liou also mentored many early-career researchers who worked with him as visiting scholars. With his passion for science and incessant pursuit of excellence in the three key areas of university faculty—namely teaching, research, and service—Liou was indeed a role model for his students and visitors. On many occasions, he encouraged early-career researchers by reciting an ancient Chinese poem: "The setting sun leans on the furthest mountains to disappear, the Yellow River flows into the sea. To see a thousand miles further, ascend another story." Liou was generous and supportive of others. During his career, he wrote numerous letters in support of other colleagues' promotions and nominations for awards or recognitions.

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The passing of Kuo-Nan Liou is a blow to atmospheric science. A great atmospheric scientist is gone. He was a true expert in many research areas, most significantly in atmospheric radiation. His remarkable scientific insight led to paradigm-shifting contributions to atmospheric science, which manifest his great creativity. Liou's efforts in teaching and mentoring students and young scientists exemplify his selflessness and generosity. It is with great sorrow for us to face that Liou departed from us, but his books and legacy will live on. As tribute to Liou for his extraordinary accomplishments in scientific research, his dedication to service for the science community, his integrity, and his generosity and kindness toward others, we would borrow some words from Margit Dirac's speech at the dedication ceremony of the Paul A. M. Dirac Science Library: "It is customary to praise those who are not with us anymore—often quite undeservedly, but not in this case. No praise will exaggerate or be too glowing."

—PING YANG, YU GU, AND QIANG FU