Professor Liou’s Primary Research Work

Atmospheric Radiation Field: The field of atmospheric radiation is concerned with the study, understanding, and quantitative analysis of the interactions of solar and terrestrial radiation with molecules, aerosols, and cloud particles in planetary atmospheres as well as the surface. Liou has developed the field through his work on the theory of radiative transfer and radiometric observations made from the ground, the air, and space. The field is closely associated with the investigation of atmospheric greenhouse effects resulting from external radiative perturbations (the sun, greenhouse gases, air pollution, etc), and the development of methodologies for inferring atmospheric and surface parameters by means of remote sensing. In recent years, global warming and remote sensing have emerged as important topics in the atmospheric and oceanic sciences. Liou’s 2nd edition of “An Introduction of Atmospheric Radiation” (2002; 1980, 1st edition) is a timely contribution that familiarizes students and researchers with the forefront of atmospheric radiation.

Radiative Transfer and Cloud Physics: Although two books have been written that address the question of “atmospheric radiation” on a fundamental level, clouds play a very minor role in these texts. The importance of clouds in atmospheric radiation is clear, since they cover more than 50% of the sky. Liou presented a monograph, “Radiation and Cloud Processes in the Atmosphere: Theory, Observation, and Modeling,” (1992) to integrate radiative transfer and cloud physics in a coherent manner and to bridge the gap between cloud-radiation and climate processes. The text also presents important topics in radiation, cloud physics, thermodynamic equilibrium, and simple climate models. The information presented in this volume is closely related to the successful development of climate models for the investigation of global climate change and of remote sensing technology for the inference of clouds and aerosols.

A Unified Theory for Light Scattering by Ice Crystals and laboratory verification: The scattering of light by spheres can be solved by the exact Lorenz-Mie theory and computation can be performed accordingly. However, an exact solution for the scattering of light by nonspherical ice crystals covering all the sizes (a few to thousands of micrometers) and shapes (solid and hollow columns, single and double plates, a plate with attachment, bullet rosette, aggregate, snowflake, dendrite, and an ice particle with rough surface) that occur in the Earth’s atmosphere does not exist in practical terms. Liou first pursued the solution by means of the principle of geometric optics, which is the asymptotic approximation of the fundamental electromagnetic theory, valid for light scattering computations involving a particle much larger than the incident wavelength (Liou and Hansen 1971, Liou and Coleman 1979, Cai and Liou 1982). He and his former graduate students, Y. Takano, a research scientist at UCLA, and P. Yang, currently an Associate Professor at Texas A&M, subsequently developed a combined geometric ray-tracing and a hit-and-miss Monte Carlo approach for computing the scattering, absorption, and polarization properties of nonspherical and irregular ice crystals (Takano and Liou 1989, 1995; Yang and Liou 1995, 1996a; Liou and Takano 1994, Liou et al. 2000). A finite-difference time domain numerical solution based on a direct implementation of the Maxwell equations for light scattering by small ice crystals was further developed by Yang and Liou (1996b, 2000) to complement the geometric-optics method. By unifying these two approaches, the scattering and absorption properties of ice particles of any size and shape can be computed with precision. This is referred to as the unified theory for light scattering by ice
crystals. Without the theoretical results presented by Liou’s group, the remote sensing of cloud composition cannot be performed with sufficient accuracy (see Minnis et al. 1993a, b), and the radiative properties of ice clouds cannot be reliably determined for understanding of cirrus-climate feedback (Liou 1986, 2002, 2004).

Although Liou is a theorist, he has been pursuing laboratory light-scattering and cloud-physics experiments with a number of his associates and graduate students, primarily to verify the theory developed. He and his former graduate student B. Barkey developed a laboratory analog experiment using an aggregate assembled from sodium-fluoride (NaF) crystal columns and a rough-surface plate machined from a NaF crystal (which has optical properties similar to ice in the visible) illuminated by a polarized laser beam at 0.63 μm with an array of highly sensitive photodiode detectors mounted on a half-dome to measure the scattering pattern in 3-D space. The measurements closely follow the theoretical results (Barkey et al. 1999). Further verification was accomplished by the scattering experiments using a laboratory cold chamber where ice crystals were generated by controlling the temperature and humidity input (Barkey and Liou 2002, 2006).

**Radiative Transfer Theory and Application:** Radiative transfer covers a variety of fields, including astrophysics, applied physics and optics, planetary sciences, atmospheric sciences and meteorology, as well as various engineering disciplines. Prior to 1950, the subject of radiative transfer was studied principally by astrophysicists, although it was also an important research area in nuclear engineering and applied physics associated with neutron transport. In his landmark book, Chandrasekhar (1950) presented the subject of radiative transfer in plane-parallel (1-D) atmospheres as a branch of mathematical physics and developed numerous solution methods and techniques. In his early pursuit, 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. Later, he included a delta-function adjustment based on the similarity principle to enhance the computational accuracy of this approximation (Liou, et al. 1988). On the basis of the delta-four-stream approach, Liou and his former graduate student, Q. Fu, now a Full Professor at the University of Washington, constructed an efficient spectral radiative transfer model including the correlated k-distribution method for the sorting of absorption lines produced by numerous greenhouse gases in scattering atmospheres and the scattering and absorption properties of nonspherical ice particles (Fu and Liou 1992, 1993). Since its inception, the Fu-Liou code has been used by many as a standard method to study climate forcing due to the presence of clouds and aerosols, and has been employed by the NASA Langley Research Center for the retrieval of the atmospheric and surface radiative energy fluxes based on the data gathered from current operational (NOAA) and research (NASA) satellites.

Although not widely noted, Liou (1980, 2002, pp 295-297) proved the equivalence of the principle of invariance for finite atmospheres and the adding method for radiative transfer.

**Radiative Transfer in 3-D Clouds:** From our day-to-day experience as well as from satellite pictures, we see that a portion of the clouds and cloud systems are finite in extent or occur in the form of cloud bands. Thus, the potential effects of cloud’s 3-D geometry and inhomogeneity on the transfer of radiation must be studied to understand their impact on the radiative properties of the atmosphere, as well as to accurately interpret radiometric measurements from the ground, the air, and space. Liou is a pioneer in the development of 3-D radiative transfer theories based on the finite spherical-harmonics expansion of the intensity and
scattering phase function (Liou and Ou 1979). In a 1996 paper, Liou and Rao developed a successive order-of-scattering approach for 3-D radiative transfer, which has the advantage of applying to intricate geometry, and an innovative way of constructing a 3-D cloud extinction coefficient field from satellite observations. This study corrects the conventional plane-parallel (1-D) approach to the evaluation of the sunlight reflected and absorbed by clouds, essential to the discussion of the role of clouds/radiation in climate and climate change. Moreover, Liou and his former graduate students Y. Gu and Y. Chen derived computationally efficient semi-analytic solutions for 3-D radiative transfer based on a delta-diffusion approximation for application to broadband flux and heating calculations in cloudy atmospheres (Gu and Liou 2001, Chen et al. 2004), ideal for incorporation in climate modes to test the sensitivity of 3D and inhomogeneous cloud effects (see Gu and Liou 2006).

**Atmospheric Remote Sensing:** Remote sensing involves the interpretation and inversion of radiometric measurements of active (laser or radar) or passive (radiation from the sun or the Earth and the atmosphere) electromagnetic radiation characterized by a specific wavelength. The successful development of remote sensing must be based on the principle of radiative transfer. As a result of his expertise in radiative transfer and the availability of funding opportunities, Liou has been involved with numerous projects in atmospheric remote sensing. Three original areas are presented below.

(a) Liou discovered the principle of depolarization of a linearly polarized laser beam backscattered from water droplets and ice crystals within the context of geometric optics (Liou and Lahore 1974). While the backscattering from a symmetrical sphere retains the polarization state of the incident energy, the backscattered energy from a nonspherical ice crystal, due to anti-symmetry with respect to a line electric vector, produces a cross (perpendicular) polarization component, referred to as depolarization. This provides a powerful means of distinguishing between ice and water clouds, as well as of identifying the orientation property of ice particles from laser radar (lidar). His research associate, K. Sassen, now a Professor at the University of Alaska, further developed this depolarization concept for the detection and differentiation of clouds in the atmosphere using lidar and has become a distinguished scientist in this area.

(b) Although temperature, humidity, clouds, and precipitation have been routinely observed from satellites, the atmospheric heating rate, which has been conventionally calculated by a radiative transfer model, has not been directly measured from the existing satellite radiometers. Liou and his former graduate student Y. Xue, now a Professor of Geography at UCLA, 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 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 and Xue 1988). See also Liou and Ou (1987), Liou (2002), and Feldman et al. (2006). This presents a future challenge in satellite remote sensing and direct assimilation of the measured heating rate data in weather and climate models.

(c) The future U.S. operational satellite system, the National Polar-orbiting Operational Environmental Satellite System (NPOESS), will be a combination of the NOAA and the Air Force DMSP satellite series to take place in about 2010. Through its subcontractors, Northrop Grumman (TRW) and Raytheon, Liou and his associates, S. C. Ou and Y. Takano, were invited to participate in the cloud remote sensing program in its early phase and developed an inversion algorithm for the retrieval of cloud composition and height on the basis of a set of carefully
selected visible and infrared spectral channels. These channels form the baseline design for the future U.S. operational cloud remote sensing instrument, in particular, the Visible-Infrared Imaging-Radiometric Suites (VIIRS).

**Remote Sensing of 3-D Inhomogeneous Clouds:** The capability of present satellite radiometers is limited to the mapping and retrieval of clouds and aerosols in the horizontal (x-y) plane, without the vertical information. Liou’s interest in 3-D radiative transfer led him to develop a remote sensing technology for the mapping and imaging of 3-D inhomogeneous clouds, which is important in the analysis of the atmospheric heating profile for weather and climate models. In the 1990s, technological advances led to the development of millimeter-wave radars, which can penetrate through clouds and enhance their study. In particular, with the incorporation of a Doppler component, the vertical cloud water content and particle size can now 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 3-D inhomogeneous cloud fields in a mesoscale grid. Liou and his associates applied this methodology to the data collected by the DOE’s Atmospheric Radiation Measurement (ARM) Program in Oklahoma, and the results were successfully verified from the particle size distribution independently derived from collocated and coincident measurements by aircraft optical probes (Liou et al. 2002). The 3-D imaging of clouds is considered to be a significant accomplishment for the DOE/ARM program and Liou’s paper 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.

**Contribution to Clouds/Aerosols and Climate Research:** Clouds play a pivotal role in modulating the energy budget of the Earth-atmosphere system, and hence climate and climate change as well. Clouds reflect the incoming sunlight to space referred to as the solar albedo effect. At the same time, they also trap the outgoing thermal infrared radiation emitted from the Earth and the lower atmosphere referred to as the infrared greenhouse effect. The competition of these two effects determines whether the Earth-atmosphere system undergoes heating or cooling. Cirrus are thin, wispy clouds that appear at high altitude, consist of ice crystals, and are unique in producing the infrared greenhouse effect. In a paper entitled “Influence of Cirrus Clouds on Weather and Climate Processes: A Global Perspective” (1986), Liou demonstrated that these 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 simple climate models with varying degrees of complexity. Since the publication of this paper, numerous composite field experiments have been designed and conducted to collect data to define the impact of cirrus on the radiation budget and climate.

Recognizing the importance of cloud microphysical processes in climate, Liou developed a 1-D cloud-precipitation-climate model to investigate the potential link between the perturbed cloud particle size distributions and precipitation produced by greenhouse warming/air pollution (Liou and Ou 1989). They discovered that 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 hypothesis linking cloud particle size and precipitation in climate change is now referred to as the second indirect
climate forcing in aerosol-cloud feedbacks (Intergovernmental Panel on Climate Change 2001, section 5.3.5).

More recently, Liou and his associates conducted numerical simulations involving the increase of anthropogenic aerosols in China in the last 50 years on precipitation anomaly employing the UCLA atmospheric GCM. It is showed that increased aerosol optical depths in China lead to a noticeable increase in precipitation in the southern part of China in July due to the cooling in midlatitude and produce a precipitation pattern referred to as “north drought/south flooding” that has been frequently observed in China during the past 50 years. Also, 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 (Gu et al. 2006).

Radiation and Turbulence Interaction in Cirrus Clouds: In addition to his accomplishments in radiative transfer, remote sensing, and climate application, Liou contributed to the basic understanding of microphysics, radiation, and turbulence interactions in clouds. In his 1992 text, Chapter 4, “Theory, Observation, and Modeling of Cloud Processes in the Atmosphere,” is entirely devoted to this subject. Moreover, Liou and his former graduate student, Y. Gu, constructed a 2-D model to understand the evolution of cirrus clouds (Gu and Liou 2000). This paper 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 in 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. This work provides a foundation for parameterization of the cirrus cloud formation in climate models, in which these clouds must be treated as sub-grid processes.