surprising that he won the outstanding teacher award in the UCLA physics department four times, which for him was a source of great pride.

He began his career with a series of laboratory experiments that compared seismic theory with observations. His laboratory skills led to his codiscovery with George Kennedy of thermoluminescence dating. In 1956 his work took a theoretical turn, resulting in a famous paper that led to the representation theorem for calculating ground motions arising from body forces and motions on a surface such as an earthquake fault. In that paper, Knopoff extended to the elastodynamic problem Kirchhoff's retarded potential solution to the wave equation, thereby providing the elastic analog to Green's theorem.

Knopoff often used his sense of humor to emphasize a point. A famous paper with the shortest title possible, "Q," is a paper that describes in detail the attenuation of elastic waves in the laboratory and in Earth and then presents a thorough theoretical analysis of several mechanisms that might explain such attenuation. Published in 1964 in *Reviews of Geophysics,* "Q" continues to be widely quoted. In contrast, with John Gardner he published a paper with the remarkably long title "Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?" followed by the shortest abstract: "Yes." In 1974 he copyrighted his version of Mahler's *Das Lied von der Erde* in two (Earth) movements, composed of computer-generated music. The first movement was based on seismicity from the 1952 Kern County, California, earthquake, and the second was an accelerated digital recording of the normal modes of the Earth.

As his career developed, Knopoff moved from the laboratory to the field. He pioneered the installation of temporary long-period seismograph arrays with an experiment in the European Alps reported in 1966. With colleagues he developed an ultralong-period seismometer installed at the South Pole that made the first measurements of solid Earth polar tides and vibrational modes of the Earth unaffected by splitting due to rotation and ellipticity. His group used surface waves to define the main structures of plate tectonics, including the thickening of the lithosphere with age of oceanic plates and the very deep roots, or keels, under continental shields.

In seismic theory he has many canonical analytical expressions to his name. Of note is his (1958) elegant solution to the antiplane crack, which ranks in fame alongside the inplane (1928) Starr crack and the Eshelby (1949) circular crack. He developed efficient algorithms to solve the problem of elastic waves propagating in layered media and to compute seismograms by superpositions of normal modes. He was one of the first to recognize the applicability to the earthquake problem of modern developments in nonlinear science. The Burridge and Knopoff model (1967) of interacting springs and blocks became the basis for simulating earthquake dynamics. With Yan Kagan he developed the stochastic branching model of faulting that displays the clustering properties of earthquake catalogs including foreshocks, aftershocks, and weak clustering of main shocks, providing a theoretical basis for earthquake forecasting.

An accomplished pianist and harpsichordist, rather than choosing a professional career as a concert musician, he chose a path that explored and appreciated the richness of physics, mathematics, and the Earth as well as of music. His encyclopedic knowledge rendered a conversation with him an illumination, albeit sometimes a challenge to keep pace. He is missed both as a warmhearted person and an intellect, and he leaves a legacy of teaching and research at the highest levels that serves as a prime example of unselfish cooperation.

He is survived by his wife, Joanne; children Katie, Rachel, and Michael; and a grandson.

—Paul Davis and David Jackson, UCLA; E-mail: pdavis@ucla.edu; and Freeman Gilbert, University of California, San Diego

MEETING

Estimating Uncertainties in Watershed Studies

Quantifying Uncertainty in Ecosystem Studies (QUEST) Workshop: Uncertainty in Hydrologic Fluxes of Elements at the Small Watershed Scale; Boston, Massachusetts, 14–15 March 2011

PAGE 220

Small watersheds have been used widely to quantify chemical fluxes and cycling in terrestrial ecosystems for about the past half century. The small watershed approach has been valuable in characterizing hydrologic and nutrient budgets, for instance, in estimating the net gain or loss of solutes in response to disturbance. However, the uncertainty in these ecosystem budget calculations is generally ignored. Without uncertainty estimates in watershed studies, it is difficult to evaluate the significance of observed differences between watersheds or changes in budgets over time, and erroneous conclusions may be drawn. The historical lack of attention given to uncertainty has been due at least in part to the lack of appropriate analytical tools and approaches. The issue of uncertainty has been confronted more rigorously in other disciplines, yet the advances made have not been comprehensively applied to biogeochemical input-output budgets. In recent years, there has been growing recognition that estimates of uncertainty are essential for coming to sound scientific conclusions, identifying which budget components most need improvement, and developing more efficient monitoring strategies, thereby maximizing information gained per unit cost.

A working group called Quantifying Uncertainty in Ecosystem Studies (QUEST) was recently established to better address the issue of uncertainty in biogeochemical studies. The inaugural QUEST meeting was funded by the Long Term Ecological Research Network Office with support from the U.S. National Science Foundation. Fifteen specialists working at the small watershed scale, including experts on uncertainty analysis, hydrology, and ecology, met to develop a strategy for conducting a synthesis of uncertainty in input-output budgets of major elements across small watersheds with diverse characteristics.

The meeting began with a series of short site presentations, followed by a discussion of uncertainty in streamwater flux, precipitation flux, and potential workshop products. The following sources of uncertainty were identified: measurement error (e.g., laboratory analysis of solute concentrations), sampling error (especially temporal variation in the case of stream chemistry and spatial variation in the case of precipitation amounts), regression or conversion error (e.g., stage-discharge relationship), and model selection error (e.g., multiplying a weekly concentration by a weekly discharge versus including additional predictor variables to describe changes in chemistry during the week). The group recognized that among the selected watersheds, some sources of uncertainty are particularly challenging to quantify, such as blowing snow, groundwater, and melting glaciers. Key decisions were made about the synthesis, including the sources of uncertainty that would be evaluated, ions to include in the analysis, and the time frame that would be used.

This initiative will help increase awareness of different methods for including uncertainty in ecosystem budgets and provide the biogeochemical research community with the theoretical and analytical tools to analyze uncertainty in many types of measurements. These efforts will help QUEST achieve its primary goal, which is to facilitate a cultural change in which uncertainty analysis becomes an accepted and expected practice in biogeochemical studies.

Further information about this organization can be found on the QUEST Web site (http://www.quantifyinguncertainty.org). Those interested in participating in QUEST should e-mail quantifyinguncertainty@gmail.com.

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