

Sean Twomey was born in Cork County, Ireland, and received his B.Sc., M.Sc., and Ph.D. in physics from the National University of Ireland, Galway. He held research appointments with the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, the U.S. Weather Bureau, and the Naval Research Laboratory before coming to the University of Arizona's Department of Atmospheric Sciences, first as a visiting professor at various times between 1973 and 1975, followed by a full academic appointment in 1976 until his retirement in 1990.

While at CSIRO, Sean published many early papers on aerosol microphysical properties, including both theoretical and experimental work on nucleation theory, cloud condensation nuclei, weather modification, and electrification of individual cloud drops. Among other contributions, he developed a simple analytic relationship between updraft velocity, aerosol cloud condensation nuclei spectra, and the resulting droplet concentration in liquid water clouds that has been highly influential in cloud physics.

When he first came to the United States to work at the U.S. Weather Bureau and later the Naval Research Laboratory, he turned his attention to the new field of remote sensing and the spectral variation of scattering and absorption in the atmosphere. He was among the first to suggest the use of scattering in the atmosphere to infer the vertical distribution of ozone by ultraviolet measurements from a satellite. This led him to the exploration of the solution of quadrature formulas that reduce Fredholm equations of the first kind to systems of linear equations. His pioneering 1963 paper, often referred to as the constrained linear inversion or Phillips-Twomey inversion method, has been extensively used in numerous applications ever since. He noted the fact that, even given perfect accuracy, the inversion of near-singular systems had often quite extraordinary error magnification powers. Furthermore, the increase in the number of data points contributes to higher frequencies being introduced, and therefore leads to worsening rather than improving the discrepancies between the "solution" and the expectations. He therefore often refuted the argument that the use of more wavelengths in a remote-sensing problem necessarily produces more pieces of "independent" information.

He simplified Phillips's two-matrix inversion formula to a single matrix inversion, and his well-written and relatively short paper was the only one he ever typed in his career (hence contributing to its short length). He applied his inversion method to the determination of aerosol size distributions from diffusional decay and later to transmission through nuclepore filters, once again turning to his interest in aerosol particles and their microphysical properties. He also applied it to the indirect measurements of atmospheric temperature profiles from satellites and the mathematical complexity of this inversion problem.

In the field of atmospheric radiation, Twomey was one of the first to publish computational solutions to the equation of radiative transfer (now known as the adding/doubling method) in his paper on matrix methods for multiple-scattering problems in the *Journal of the Atmospheric Sciences* in 1966. At the end of the introduction he noted: "After the first draft of this paper was completed, the authors read a monograph by van de Hulst (1963) in which an operator notation was developed and applied to the multiple scattering problem. The methods described in this paper and those developed by van de Hulst are essentially equivalent." He later applied this "matrix operator" method to the computation of transmitted and reflected radiation from optically thick cloud layers in anticipation of developing methods to retrieve cloud optical thickness and some microphysical properties of the cloud droplets. Although initially discouraged by the lack of microphysical (cloud droplet size distribution) sensitivity, he later pursued derivation of the cloud optical thickness and effective radius of clouds from reflected solar radiation measurements, again blending his theoretical and experimental capabilities.

In spite of his many contributions to atmospheric radiation, aerosol and cloud physics, and inversion mathematics, he will perhaps best be remembered for a seminal paper he published nearly 40 years ago: "Pollution and the Planetary Albedo," in *Atmospheric Environment*. This paper first introduced the concept of enhanced cloud nuclei from anthropogenic pollution

SEAN TWOMEY
1927–2012

IN MEMORIAM

WILLIAM W. AIRD
1922–2012

ROBERT D. BOUDREAU
1931–2012

ARTHUR GULLIVER
1921–2013

JERRY MAHLMAN
1940–2012

DEAN R. MORFORD
1954–2013

that may increase the amount of solar radiation reflected by clouds, for which he later received the Haagen-Smit Prize from the publisher of *Atmospheric Environment* in recognition of this outstanding paper. In a career of groundbreaking discoveries, it is this paper that may be Sean's most enduring for the phenomenon that now bears his name, the Twomey Effect.

He subsequently wrote two very influential textbooks: *Introduction to the Mathematics of Inversion in Remote Sensing and Indirect Measurements* (1977) and *Atmospheric Aerosols* (1979). For these and other achievements, Twomey received the AMS Carl-Gustaf Rossby Research Medal in 1980 "for extensive contributions to the development of many areas of atmospheric science, including aerosol and cloud physics, radiative transfer, and remote sensing from satellites."

It will be many years before the full impact of Professor Twomey's contributions to the atmospheric sciences is understood. Sean had a unique and comprehensive understanding of the science and mathematics that he helped pioneer. It was always a great

pleasure to hear him explain complex concepts in his singularly clear, intuitive, and enthusiastic style. His legacy will be carried on by a generation of scientists that he influenced, from colleagues, to students, to a much greater number of scientists who never met Sean because he seldom traveled—unless there was a horse race in town. For those of us fortunate to have shared a beer with Sean, it was abundantly clear that the years were marked not by the orbit of the Earth about the Sun, but by winners of the Preakness, the Melbourne Cup, and the Irish Derby, among many, many others. He will be missed.

Twomey is survived by his four children, Adele Twomey of Sydney, Australia; Kieran S. Twomey of San Diego, California; Tim J. Twomey of Cobb, California; and Damian P. Twomey of Tucson, Arizona; plus many grandchildren, nieces, and nephews. He was preceded in death by his parents, his lovely wife, Marie J. Twomey, and his eldest son Patrick Twomey.

—MICHAEL D. KING, PETER PILEWSKIE,
AND STEVEN PLATNICK

AMS STATEMENT

SPACE WEATHER

A Policy Statement of the American Meteorological Society

(Adopted by the AMS Council on 9 July 2013)

SPACE WEATHER DEFINITION. Space weather refers to the dynamic conditions on the Sun and in the space environment, in particular, in the near-Earth environment.

SOCIETAL IMPACTS OF SPACE WEATHER.

As our dependence on complex, advanced technology increases, so does our vulnerability to space weather. Space weather is a global-scale phenomenon with the demonstrated ability to disrupt high-frequency radio signals, satellite-based communications, navigational satellite positioning and timing signals, spacecraft operations, and electric power delivery with cascading socioeconomic effects resulting from these disruptions. Space weather can also present an increased health risk for astronauts and well as aviation flight crews and passengers on transpolar flights. The estimated cost of an extreme space weather storm could reach up to a trillion dollars with a potential recovery time of 4–10 years.¹

An extreme space weather storm is a low-probability, high-consequence event that poses risks to critical infrastructures around the world. Unlike with almost all other natural hazards, modern society lacks adequate experience in preparing for, and responding to, an extreme space weather storm. This situation is exacerbated by our heavy reliance on space-based technologies and the rapidly evolving nature of our vulnerability. A storm that degrades the electric power grid could affect not only the energy sector, but also the transportation, manufacturing, communications, banking, and finance sectors, as well as government services and emergency response capabilities.

Space weather can also impact the operation of critical infrastructure relying on space-based assets. Space weather storms can distort and disrupt signals emitted by Global Positioning System (GPS) satellites. GPS boosts productivity across many sectors of the